LATERAL EXCHANGE OF WATER AND NITROGEN ALONG A BEAVER-DAMMED STREAM DRAINING A ROCKY MOUNTAIN VALLEY

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By

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ABSTRACT

Dynamic exchange of water across the stream-riparian zone interface is important in increasing stream water transit time through basins and enhancing redox-sensitive biogeochemical reactions that influence downstream water quality and ecosystem health. Such exchange may be enhanced by beaver dams, which are common throughout low order streams in North America, Europe, and Argentina. Lateral exchanges of water and nitrogen (N) were observed along a beaver dammed, third-order stream draining a 1.3 km^2 Canadian Rocky Mountain valley bottom capped in peat. Measurements of hydraulic heads and chloride concentrations from a network of 80 water table wells were used to identify areas of stream water and groundwater mixing in the riparian area, and their spatiotemporal dynamics in summer 2008. Beaver were found to be the greatest factor affecting lateral movement of channel water into the riparian area. Channel water flowed laterally into the riparian area upstream of the dams and back to the channel downstream of the dams. The hyporheic zone expanded by $\leq$1.5 m in the un-dammed reaches, but upwards of 7.5 m or more when dams were present. High contributions of stream water were found far out in the riparian area where dams were not immediately present within the stream reach, suggesting that upstream dams directed stream water into the riparian area where it travelled down valley before returning to the stream. This suggests that multiple dams create hyporheic flow paths at multiple scales. Potential mass flux calculations show the riparian area immediately downstream of the beaver dam was a source of N and dissolved organic carbon (DOC) to the stream, and a sink along the rest of the reach. Cold spots of N and DOC availability were also found along the beaver-driven flow paths in the riparian area adjacent to the dam. This pattern likely developed due to flushing of nutrients

along the beaver driven hyporheic flow vectors. This work enhances our understanding of stream-aquifer exchange and N dynamics in riparian areas, and the effects of beaver on these processes.

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LIST OF ABBREVIATIONS

α	Statistical significance level
A	Area normal to the direction of flow (m^2)
C	Dissolved nitrogen or dissolved organic carbon concentration (mg/L)
C_G	Chloride concentration of groundwater (mg/L)
C_R	Chloride concentration of riparian water (mg/L)
C_S	Chloride concentration of stream water (mg/L)
Cl^-	Chloride
CV	Coefficient of variation
DIN	Dissolved inorganic nitrogen
DNRA	Dissimilatory nitrate reduction to ammonium
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
GW	Groundwater
h_R	Riparian well hydraulic head (m)
h_S	Stream hydraulic head (m)
HW	Hyporheic water
IQR	Interquartile range
K	Saturated hydraulic conductivity (m/s)
Δl	Horizontal distance between stream stage well and riparian well (m)
L	Length of the well screen (m)
n	Number of samples
N	Nitrogen
N_{flux}	Flux of dissolved nitrogen or dissolved organic carbon (mg/day)
N_2	Atmospheric nitrogen
NO_3^-	Nitrate
NH_4^+	Ammonium
p	Statistical significance value
PVC	Polyvinyl chloride
Q_{flux}	Water flux between the stream and riparian area (m^3/s) or (L/day)
Q_S	Stream discharge (L/s)
r	Well radius (m)
R	Radius of the well screen (m)
r_S	Spearman rank correlation coefficient
r^2	Coefficient of determination
SW	Stream water
%SW	Percent stream water
T_0	Time to normalized head of 0.368 (s)

CHAPTER 1 – INTRODUCTION

Historically, streams and groundwater were believed to be two hydrologically distinct units. The stream was believed to be isolated from its drainage basin and was not biogeochemically and ecologically influenced by the flow of water through underlying sediments and discharge of water from adjacent soil and bedrock environments (Jones and Mulholland 2000). Under this paradigm, water and solutes would move in a unidirectional fashion from the watershed to the stream, where they would be subsequently removed from the watershed. In the late 1980s and early 1990s a new paradigm of stream water transport was proposed, in which water and solutes are exchanged between the stream and adjacent riparian area through multiple flow paths of subsurface transport (Fig. 1.1). This exchange of stream water with groundwater near the stream margins was termed hyporheic exchange.

This chapter provides a general review of the hyporheic literature and identifies research gaps relating to hyporheic exchange and nitrogen dynamics in the hyporheic zone. The background knowledge is then used to formulate the objectives of this thesis.

1.1 Hyporheic zone

1.1.1 Defining the hyporheic zone

The hyporheic zone is the saturated pore space in sediments beneath and laterally adjacent to a stream channel, and is strongly influenced by the interchange of ground and surface water (Triska et al. 1993; Howard et al. 2006; Figs. 1.1-1.2). The actual extent of this region is defined in many different ways, depending on the nature of the study. In an ecological context, the hyporheic zone is described as the active ecotone between the surface stream and the deep groundwater characterized by the exchange of water, nutrients, biota, and other materials (Boulton et al. 1998). Traditionally, ecologists have focused on vertical hyporheic exchange because of its importance to fish spawning habitats, and hydrologists have focused on lateral exchange (which they call bank storage) because of its importance in attenuating peak flows. Few studies have examined the hyporheic zone in its entirety.

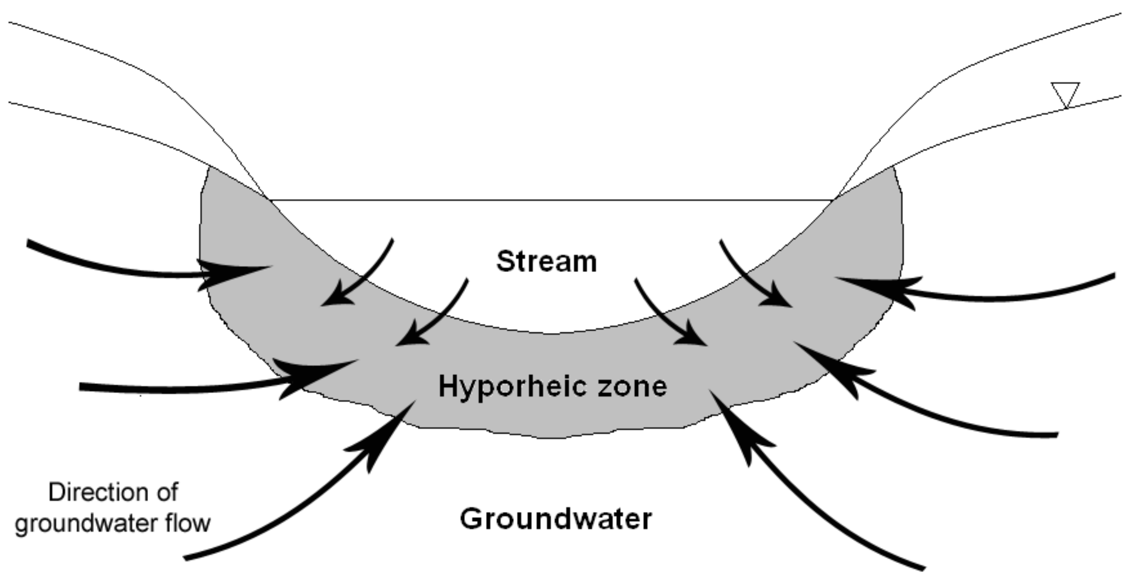

Figure 1.1. A conceptual diagram of the hyporheic zone.

Hyporheic exchange can be differentiated from larger scale groundwater and channel interactions by the flow path length and timescale of the interaction (Fig. 1.2), but both small and large hyporheic flow paths are usually present along streams. The greatest interaction with the stream usually occurs along relatively short hyporheic flow paths that return to the stream within centimeters in perennial headwater streams to tens of meters in mid-order streams (Jones and Mulholland 2000). However, the size of hyporheic zones varies among streams because stream water penetration into the bed and banks depends on many factors such as groundwater inflows, stream discharge, stream morphology, and saturated hydraulic conductivity. For example, perennial headwater streams dominated by groundwater have small hyporheic zones because groundwater inflows from adjacent hillslopes can be sufficient to maintain hydraulic head gradients toward the stream along its margin (Wondzell 2006).

Hyporheic flow paths may occur at multiple interactive scales along a stream reach. They may exist entirely within the streambed, penetrate mid-channel or point bars, flow between channels (e.g. main channels, side channels, spring channels, and tributary channels on a floodplain), or span kilometers along a floodplain (Wondzell 2006; Poole et al. 2008). These nested hyporheic flow paths have been found to be driven by variations in stream discharge and channel morphology (Wondzell and Swanson 1996a; Wondzell 2006). Although many people have recently conceptualized nested hyporheic flow, few (e.g. Wondzell and Swanson 1996a; Wondzell 2006) have actually identified these areas of multiple interactive flow paths.

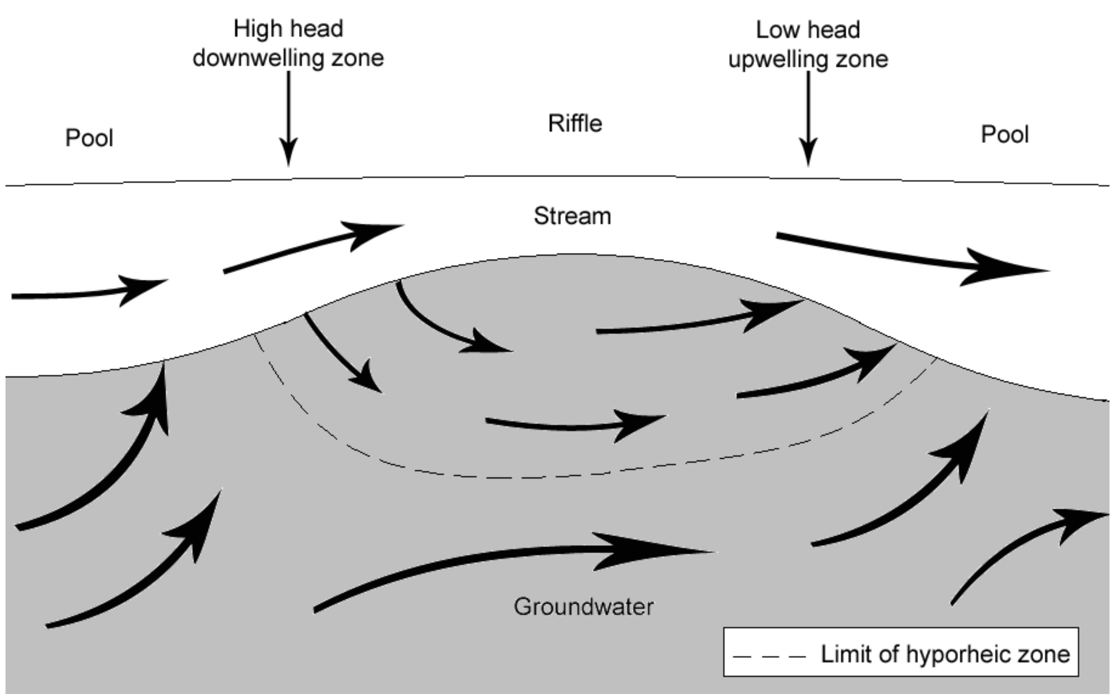

Figure 1.2. Schematic of the longitudinal hyporheic zone showing upwelling and downwelling (solid lines) within a pool-riffle sequence (modified from Howard et al. 2006).

1.1.2 Significance

Hyporheic exchange is important because it repeatedly keeps surface water in close contact with chemically reactive mineral coatings and microbial colonies on the subsurface strata, which has the effect of enhancing biogeochemical reactions that influence downstream water quality (Jones and Mulholland 2000). The redirection of water from the stream to the near-stream environment subjects solutes to alternating oxic and anoxic environments and geochemically active sediments and microorganisms, thereby increasing the potential for nutrient retention and enhanced microbial activity (Lautz et al. 2006). More specifically, groundwater can be a significant source of dissolved organic carbon (DOC) and nutrients to the hyporheic zone, particularly when the hyporheic zone is comprised of organic soils such as peat. When nutrient and DOC rich groundwater mixes with relatively warm and oxygen-rich stream water in the hyporheic zone, biogeochemical cycling is likely to be enhanced by the many organisms that permanently or temporarily inhabit the region (Howard et al. 2006). For example, Williams (1989) found that the distribution of *Diacyclops crassicaudis brachycerus* appeared to be a function of interstitial nitrate concentration.

Hyporheic exchange is important for the life cycles of many aquatic vertebrates, such as fish, amphibians, and reptiles. For example, fish eggs require well-oxygenated water and are often deposited a few centimeters in the streambed (Findlay 1995). The supply of oxygen to subsurface sediments and the consumption of oxygen within those sediments is possibly the clearest and best-known example of the importance of connections between the stream and hyporheic sediments (Findlay 1995).

Lateral hyporheic exchange, or bank storage, is important to hydrologists because it increases stream water transit time through a basin and attenuates peak flows (Whiting and

Pomeranets 1997). Increasing the residence time within a reach and contact with subsurface sediments may also result in dramatic alterations in material transported from the catchment to the receiving body of water (Findlay 1995). Therefore, it is particularly important for flood forecasts and sediment load predictions. Some stream water that enters the adjacent riparian area during bank storage may also recharge the adjacent aquifers. Understanding the mode of riparian area inundation and recharge of aquifers is critical for the management of river corridors and watersheds (Westbrook et al. 2006).

1.2 Hyporheic zone delineation

The outer limit of the hyporheic zone is essentially the maximum distance that stream water flows either laterally out of the channel or vertically beneath the stream bed to interact with the nearby aquifer before flowing back to the stream channel (Fig. 1.1). Hyporheic flow allows a river valley to become connected to its stream, so information on the extent of hyporheic flow is useful in determining how well the riparian zone is hydrologically connected to the stream. The hyporheic zone has been shown to contract in response to increased groundwater inflows and stream discharge during storms, and expand as catchments dry and stream discharge decreases (Wondzell 2006). However, most work delineating hyporheic zones has been done in catchments where the streams are either losing or gaining (i.e. Covino and McGlynn 2007), and work is needed in stream systems that have groundwater flow parallel to the stream to see whether hyporheic exchange is an important hydrological process.

The hyporheic zone can be delineated by creating streambed isotherm profiles based on temperature differences between stream and groundwater. However, measurements of hydraulic head and solute-tracer concentrations in the stream, bed, and banks are more reliable and widely used techniques to quantify hyporheic exchange. These techniques are reviewed below.

1.2.1 Hydrometric method

Hydraulic head gradients cause upwelling (groundwater flows up into the hyporheic zone) and downwelling (stream water flows down into the hyporheic zone), and can occur multiple times within one stream reach (Fig. 1.2). At the reach scale, the most obvious linkage between stream and groundwater is by hydrological exchange in these upwelling and downwelling regions that form in response to reach-scale geomorphological features such as debris dams (log jams) or beaver dams. For example, vertically looping hyporheic flow paths have been shown to develop underneath beaver dams (Lautz et al. 2006) and log jams (Hill and Lymburner 1998). Flow that laterally enters and leaves the stream is similarly determined by hydraulic gradients, and can become transiently stored in the stream banks (Lautz et al. 2006).

The hydrometric method for delineating the hyporheic zone requires measurements of hydraulic heads from a dense network of wells and piezometers (termed piezometer nests) at various points in the banks and stream bed. Water fluxes across a stream bed are calculated on the basis of two-dimensional contour maps of hydraulic head generated from estimates of hydraulic conductivity of near-channel sediment and application of Darcy's equation to the water level measurements (Jones and Mulholland 2000). The spatial extent of the hyporheic zone can be inferred by mapping hydraulic head contours and examining which flow paths receive their water from the stream and return to the channel a short distance downstream. From such analyses, hyporheic flow paths can be distinguished from groundwater flow paths, which enter or leave the stream reach only once.

1.2.2 Tracer methods

The use of solute tracers allows for more accurate hyporheic zone delineation than the hydraulic head technique where only inferences about the extent of the hyporheic zone can be made from flow nets. Using solute tracers to delineate the hyporheic zone requires mapping the riparian water concentrations of natural or artificial tracers at varying distances from the stream channel. The commonly used stream-tracer approach involves the injection of a conservative solute tracer into a stream at a constant rate until the tracer concentrations reach a plateau. This approach provides information about the storage and retention capabilities of the hyporheic zone. However, tracer tests are labor intensive, can often take weeks for the downstream tracer concentration to reach a plateau, and can become logistically difficult at high discharge or during periods of changing stream discharge (Wondzell and Swanson 1996a). Typically, they are used just once or twice during a field season (e.g. Wondzell 2006), which provides little information about temporal variations of the hyporheic zone.

A wide variety of tracers have been used to delineate the boundaries of the hyporheic zone, including DOC, microbes, and different solutes. Chloride (Cl^-) is an effective tracer because it is biologically inert and does not readily absorb to sediments (Triska et al. 1989; Hill et al. 1998; Hill and Lymburner 1998). The boundaries of the hyporheic zone also have successfully been delineated by determining the relative proportions of stream and groundwater in porewater samples using other conservative tracers, such as bromide (Hill et al. 1998; Ryan and Boufadel 2006), or non-conservative tracers, such as interstitial organisms (Williams 1989; Franken et al. 2001). Natural environmental tracers are widely used to determine event and pre-event runoff components contributing to stream discharge. However, very few studies (e.g. Hill et al. 1998; Hill and Lymburner 1998) have applied this method to delineate the hyporheic zone based on differences in background chemical composition of stream and groundwater. Hill and his colleagues have found that using naturally occurring Cl^- as a tracer was an effective method for determining the maximum extent of stream-aquifer interaction at a site in southern Ontario due to large differences in stream water and groundwater Cl^- concentrations (Hill et al. 1998; Hill and Lymburner 1998). In their method, riparian water samples are obtained at various distances and depths from the stream channel, and are compared to the stream and groundwater tracer signatures using a simple mixing equation that determines the proportion of riparian water that comes from the stream. Interstitial riparian water containing 10-98 % stream water has been previously used to delineate the hyporheic zone (Triska et al. 1989; Hill et al. 1998; Hill and Lymburner 1998). The application of this equation is based on certain caveats outlined by Hill and Lymburner (1998) and Hoeg et al. (2000): (a) there is a significant difference between the tracer concentrations of the stream and groundwater components; (b) the tracer concentrations are constant in space and time (at least the time over which the samples are taken); (c) water in the hyporheic zone is only from two sources, stream and groundwater; and (d) the tracer mixes conservatively.

Environmental water isotopes, i.e. oxygen-18, deuterium, or tritium are commonly used to separate water based on its relative age (e.g. event versus pre-event water) (Sklash and Farvolden 1979). However, they are not particularly useful for hyporheic zone delineation in many stream systems where groundwater has a short resident time in the watershed, and thus the stream and groundwater have similar isotopic compositions. Isotopic content varies depending on the type of precipitation (e.g. rain, snow, hail, etc.), the type of precipitation system (e.g. frontal, orographic, convective), and the intensity and duration of the event (Kendall and McDonnell 2000). Over a long period of time, it is the accumulation of water from these precipitation events that gives groundwater an isotopic signature distinct from a single event. Due to the relatively rapid turnover of water in the hyporheic zone, assumption (a) would be violated because distinct end-member isotopic signatures would not be evident in the stream and nearby aquifers. For example, Wondzell and Swanson (1996a) estimated that the mean resident time of water stored within the aquifer for the floodplain of a 4^{th}-order mountain stream was 30 days during baseflow periods, which is not long enough to create a distinct groundwater isotope signature.

1.2.3 Temperature method

Delineation of the hyporheic zone can also be done by creating streambed isotherm profiles. Although stream water temperature varies considerably over time, groundwater temperature stays relatively constant, and it is this temperature difference between stream water and groundwater that provides the basis for using temperature probes to map patterns in the streambed (White et al. 1987). The data from streambed temperature profiles suggests that stream water enters the bed and gradually mixes with cooler groundwater (White et al. 1987). This has been supported by Lapham (1989), who found that upwelling decreased the depth of the hyporheic zone affected by stream temperature fluctuation, and downwelling increased the depth. However, this method requires the installation of an extensive temperature sensor array and is difficult to use because temperature patterns have been shown to be variable when the stream bed had irregularities such as large rocks occurring in and on the bed (White et al. 1987).

1.3 Controls on expansion and contraction of the hyporheic zone

The spatial extent of the hyporheic zone varies temporally in response to changes in both the stream level and the valley water table caused by variations in baseflow, precipitation events, and hydraulic conductivity of the bed and bank material. For example, Wondzell and Swanson (1996a) found that stream water penetration into the hyporheic zone declined 30 to 50 percent during the wet season because the higher baseflow levels caused a hydraulic gradient that opposed extensive movement of stream water into the hyporheic zone. A similar phenomenon would likely occur in response to precipitation events large enough in magnitude to raise the water table. There have been few studies, however, that have attempted to relate the magnitude of hyporheic exchange with the magnitude of stream and groundwater discharge events (Wondzell and Swanson 1996a). The variable source area concept, founded by Hewlett and Hibbert (1967), refers to the expansion of the saturated surfaces during storm events and explains how runoff is produced from saturated areas on hillslopes that expand and contract in response to storm events. It is expected that aquifer-stream connections operate in much the same way, meaning that the hyporheic zone may expand during high stream flow events and contract in response to a raised groundwater table or low stream flows.

The type of porous media within the hyporheic zone also influences the extent to which stream-aquifer interactions occur due to variations in hydraulic conductivity. By injecting sodium bromide (NaBr) tracer into a stream, Ryan and Boufadel (2006) found that higher tracer concentrations were observed in areas where the hydraulic conductivity was higher; low tracer concentrations were observed in lower hydraulic conductivity areas. However, most of these hyporheic zone studies have been carried out in alluvial stream systems, while few have examined hyporheic exchange in peatland soils. Uneven microtopography of the soil surface combined with spatial heterogeneity of hydraulic conductivity was also found to promote greater vertical exchange between surface water and porewater in very poorly consolidated surface soils typical of wetlands (Rutherford and Nguyen 2004).

1.4 Nitrogen dynamics in the hyporheic zone

Nitrogen (N) is important to both terrestrial and aquatic ecosystems because it is necessary for healthy plant and microbial growth, and therefore can limit ecosystem productivity.

A large number of studies have focused on N biogeochemistry due to the rising levels of anthropogenically derived N that may disrupt the N cycle causing increased leaching of nitrate (NO_3^-) and dissolved organic nitrogen (DON). Increased leaching of these N species could lead to the eutrophication and acidification of receiving waters (Cooper et al. 2007), which could potentially have serious effects on the health and functioning of aquatic ecosystems and on the quality of drinking water.

The N cycle within the hyporheic zone is regulated by interactive hydrologic, chemical, biologic, and geologic factors. For example, water temperature directly affects the rates at which microbes and plants process N, because at low temperatures the metabolic biochemical kinetics of the organisms are impeded (Limpens et al. 2006). Therefore, the influx of warmer stream water into the hyporheic zone increases reaction rates within the porous media. Also, DON concentrations are highest in warm summer months because of the enhanced turnover and release of organic matter in soils and surface waters, while the opposite is true for NO_3^- concentrations as they are significantly reduced during the summer by biological uptake. (Cooper et al. 2007).

The entry of stream water into the hyporheic zone forms gradients of essential biological energy and nutrients (DO, DOC, DON, NO_3^-, and NH_4^+) that reflect linkages between the biotic metabolism and hyporheic hydrodynamics (Triska et al. 1993). Much of the complexity of the N cycle is a result of oxygen availability (DO) and its spatial variability within the hyporheic zone. Some biogeochemical processes are not oxygen sensitive, whereas others prefer aerobic conditions (i.e. nitrification) or anaerobic conditions (i.e. dissimilatory nitrate reduction and denitrification). Researchers have examined patterns in N chemistry in the hyporheic zone in gravel-bed streams. From this work, Triska et al. (1989) developed a conceptual model (Fig.

1.3) outlining the general patterns in N chemistry within the hyporheic zone of Little Lost Man Creek, a gravel–cobble stream with low concentrations of inorganic N. Dominant N processes vary between sites because of variations in channel characteristics and soil types. This model provides a useful template for generating hypotheses about patterns of N chemistry for hyporheic zones in other types of stream environments.

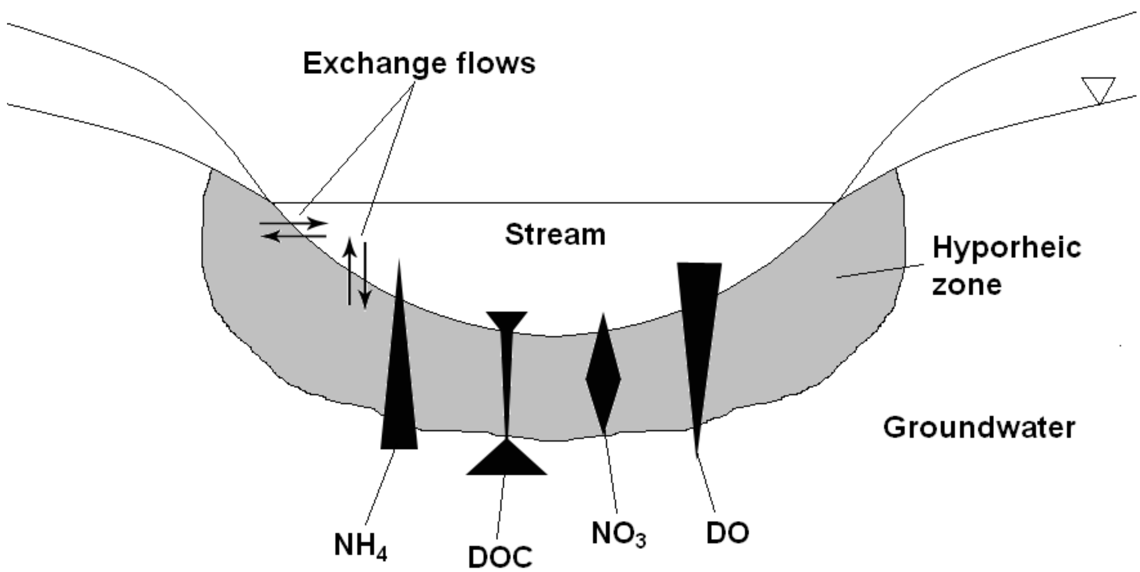

Figure 1.3. A conceptual model of patterns in nitrogen chemistry within the hyporheic zone of Little Lost Man Creek (modified from Triska et al. 1989).

In Triska's model, the channel zone is the site of greatest aerobic metabolism and associated nutrient uptake because water in the channel has free gas exchange with the atmosphere and has variable water, solute, and oxygen exchange with the hyporheic zone beneath it (Triska et al. 1989). NO_3^- production in the hyporheic zone depends on oxygen availability and may either increase or decrease along hyporheic flow paths. If interstitial water is well oxygenated, nitrification tends to prevail and the hyporheic zone is a source of NO_3^- to the stream. In contrast, anoxic systems tend to be dominated by denitrification as long as there is a carbon source available (Jones and Holmes 1996). If NO_3^- is transported to low-DO regions in the hyporheic zone, it can either be denitrified or reduced to NH_4^+ in the presence of DOC (Triska et al. 1993). NO_3^- that is denitrified to N_2 will result in a permanent loss of N from the system, whereas NO_3^- that is reduced to NH_4^+ can continue to be involved in hyporheic N transformations. Hill et al. (2004) suggest that organic-rich soils occurring below the water table can sustain significant denitrification potential rates due to the nearly unlimited availability of C.

The relatively anoxic groundwater is generally a significant source of DON, NH_4^+, and DOC to the hyporheic zone, especially in organic soils. The low DO limits nitrification but not ammonification, resulting in low concentrations of NO_3^- and high concentrations of NH_4^+ and DON. NH_4^+ that enters the hyporheic zone is sorbed to clay sediments, and under aerobic conditions, nitrifying bacteria on the sediments oxidize NH_4^+ to NO_3^- (Triska et al. 1993). Therefore, it is expected that NH_4^+ and DON concentrations would decrease as hyporheic water is transported closer to the channel where oxidizing conditions facilitate nitrification (Triska et al. 1989). For example, Hill et al. (1998) found reduced DO and NO_3^- concentrations and increased NH_4^+ concentrations with depth in downwelling areas of a pool-riffle sequence. In addition, they also found that the mixing of NH_4^+-rich relatively anoxic groundwater with channel water in areas of upwelling produced an overall increase in NH_4^+ concentrations and a decrease in DO concentration with distance downstream beneath the riffles.

The importance of these subsurface processes to the stream ecosystem is determined by the quantity of nutrients added to the stream and the chemical form of the added nutrients (Wondzell and Swanson 1996b). Even if the flux of nutrients moving to the stream is a small fraction of the nutrient flux in the stream channel, these nutrient inputs can be very important to maintaining the in-stream nutrient balance (Greenwald et al. 2008). The N form is determined by the N transformations occurring in relation to the mixing of stream and groundwater, and because the N fluxes are influenced by the quantity of hyporheic water exchange, the amount of N flushed to the stream will likely be affected by variations in baseflow and stream discharge. For example, Wondzell and Swanson (1996b) found that the greatest hyporheic N flux occurred during fall storms and was dominated by NO_3^-, whereas fluxes were dominated by DON in winter and spring, and NH_4^+ and NO_3^- were more important in summer and fall.

Flushing of nutrients can result in elevated N concentrations in the stream, which can occur over an extended period of time. The idea that specific locations in the landscape (or short periods of time) may have significantly higher and lower concentrations or biogeochemical reaction rates is not new, but the terms 'hot and cold spots' and 'hot and cold moments' have only recently been introduced to describe these locations or times. Hot spots are defined as areas that show disproportionately high concentrations or reaction rates relative to the surrounding area (McClain et al. 2003), whereas hot moments are defined as short periods of time that show disproportionately high concentrations or reaction rates relative to longer intervening time periods (McClain et al. 2003). Alternatively, areas of the landscape or time periods with disproportionately low concentrations or reaction rates are referred to as cold spots and cold moments (Allan et al. 2008; Vidon et al. 2009). Areas of converging hydrological flow paths, such as the hyporheic zone, have been found to be areas of increased biogeochemical activity because each water source carries materials essential to the reaction (McClain et al. 2005). For example, elevated biogeochemical reaction rates or hot spots have been found at an upland-peatland interface during periods of episodic hydrological connection (Mitchell and Branfireun 2005), in the riparian area of headwater agricultural streams with varying organic content (Hill et al. 2004), and in a semiarid riparian zone during monsoonal flooding (Meixner et al. 2007; Sponseller 2007; Harms and Grimm 2008). Recent work has shown riparian zones can serve concurrently as both a hot spot for biogeochemical transformations and a cold spot for contaminant transport to streams or vice versa (Vidon et al. 2009).

1.5 Beaver and the hyporheic zone

Beaver (*Castor canadensis*) are the largest rodents in North America and are ubiquitous in first to fifth order streams throughout most of North America (Figs. 1.4). They live in small, extended-family units called colonies, typically containing the adult pair, young from the current year (i.e. kits; usually 2 to 4 per litter), and young of the previous year (i.e. yearlings) (Baker and Hill 2003). Established colonies inhabit discrete and defended territories, so it is typical to find only a few colonies inhabiting a large valley bottom (Baker and Hill 2003). Prior to European settlement in North America, the beaver population was estimated to be 60-400 million (Seton 1929), but drastically decreased in numbers due to the demand for beaver pelts. Naiman et al. (1988) estimates current beaver populations to be 6-12 million, but habitat loss and other causes have severely restricted populations in many areas. In many areas in the Rocky Mountains, beaver may depend entirely on willow to supply winter forage and building material (Baker and Hill 2003).

Figure 1.4. Beaver (*Castor canadensis*) (photo credit: C. Westbrook 2004).

Beaver can have dramatic and important effects on an ecosystem by causing physical state changes in biotic or abiotic material, which directly or indirectly control resource availability (Baker and Hill 2003). Beaver are capable of creating wetlands, and can drastically influence the hydrologic processes in riparian areas of low order streams that can be dammed (Westbrook et al. 2006). The most well studied effects of beaver on stream ecosystems are the retention of sediment, organic matter, and water by beaver dams, as well as the increase in wetted surface area, alteration to riparian zones, and the modification of stream nutrient cycling and decomposition dynamics (Naiman and Melillo 1984). Beaver dams may enhance hyporheic exchange by creating artificial pool riffle sequences and decreasing stream water velocity (Lautz et al. 2006), which are two physical stream characteristics known to enhance hyporheic exchange (Wondzell and Swanson 1996a). By raising the water in the stream and subsequently raising the adjacent water table for extended periods of time, beaver can increase the stream-aquifer interactions and alter the hydraulic gradients within the stream banks and bed. For example, Lautz et al. (2006), Janzen (2008), and Hill and Duval (2009) found that small debris dams divert water temporarily into the subsurface, where it travels along short hyporheic flow paths, returning to the channel immediately below the dam. In turn, this may result in greater connectivity between the stream and surrounding aquifers. However, very few studies have examined the influence of beaver on hyporheic zone extent, particularly across a span of stream types with varying substrate types.

Beaver dams have the potential to greatly alter downstream water quality by intercepting runoff from a watershed before it enters downstream ecosystems (Margolis et al. 2001). For example, Naiman and Melillo (1984) found that a beaver-modified section of stream in Quebec accumulated 10^3 times more total N than before alteration. Since dams are expected to increase the extent of the hyporheic zone, they may also enhance biogeochemical transformations occurring around a stream, which can increase the productivity of the surrounding habitats and influence water quality to downstream areas. By increasing the length of the hyporheic flow paths, and thus the hyporheic retention time, nutrients and organic matter will have more opportunity to interact with biologically reactive sediment, which will fundamentally influence nutrient retention and losses from watersheds (Baker and Hill 2003).

Beaver dams create vertical upwelling and downwelling zones similar to pool-riffle sequences, so it could be expected to observe similar trends in water storage and N chemistry. Dams disperse stream energy, which decreases stream velocity and the rate of downstream solute transport, increases solute retention, and reduces solute uptake lengths (Trotter 1990; Lautz et al. 2006). Therefore, raising the stream stage for extended periods of time promotes greater movement of stream water into adjacent subsurface zones, and increases N transformations associated with stream-aquifer mixing.

CHAPTER 2 – STUDY OBJECTIVES

For the last few decades, studies of the interaction of groundwater and surface water have concentrated primarily on groundwater and stream connections (i.e. hyporheic flow) in alluvial systems (i.e. Franken et al. 2001, Calles et al. 2007). Few studies have examined hyporheic flow in other physiographic settings (Hill and Lymburner 1998) or ones dammed by beaver (Lautz et al. 2006). Further, while hyporheic exchange is a three dimensional process, most studies have only focused on the vertical extent of the hyporheic zone, rather than its lateral extent. This is probably because they have been conducted primarily by ecologists who are interested in applying their knowledge to predicting locations suitable for fish spawning (e.g. Calles et al. 2007). Knowledge of the dimensions of the hyporheic zone and the proportion of stream water and groundwater present at various locations within this zone provides an essential template for the analysis of solute chemistry; however, many hyporheic zone studies do not have a good understanding of these parameters (Hill and Lymburner 1998). Some recent studies have quantified nutrient availability and/or cycling rates in the near stream environment (Harms and Grimm 2008). However, it is difficult to make assumptions that the biogeochemical processes occurring are in fact attributed to hyporheic exchange because the extent of the hyporheic zone is variable along a stream reach. Rarely are measurements of hyporheic zone extent, water fluxes, and nutrient availability made simultaneously. Thus, the objectives of this study are to:

1) spatially and temporally delineate the lateral hyporheic zone of a beaver dammed stream;

2) examine patterns in N chemistry in relation to the mixing of stream and groundwater and availability of DOC; and
3) estimate potential N fluxes across the stream-riparian interface.

CHAPTER 3 – METHODS

3.1 Study site

The study was conducted within Sibbald Research Basin, a ~1.3 km^2 mountain valley in Kananaskis, Alberta (Fig. 3.1). Bateman Creek is a third order, low to medium gradient meandering stream that drains the ~500 m wide lacustrine valley capped by peat (Fig. 3.1). Peat reaches >5 m deep in some areas of the basin and is underlain by clay and gravel. Bateman Creek is dammed by many beaver dams throughout its length – dams range in size from a few meters to several hundred meters long, and tens of centimeters to about three meters high. The larger ones are easily observed on aerial photographs (Fig. 3.1).

The climate at Sibbald Research Basin (~1485 m elevation) is transitional between Cordilleran and Continental, and has warm winter temperatures due to frequent Chinook activity. For 1975 to 2008, air temperature recorded at the University of Calgary Biogeoscience Institute (1390 m elevation and ~ 17 km from the field site) averaged -6.7ºC for January, 14.5ºC for July, and 3.5ºC annually. Mean summer temperature (May to August) was 11.8ºC for 1975 to 2008, and 11.6ºC in 2008. Annual precipitation recorded at the University of Calgary Biogeoscience institute averaged 661 mm between 1975 and 2008, with 61% falling as rain.

Sibbald Research Basin is located in the Montane Cordillera ecozone. The northern half of the valley is vegetated by willow (*Salix* spp.), sedges (*Carex* spp.), *Sphagnum* spp., bog birch (*Betula glandulosa*), dwarfed white spruce (*Picea glauca*) and black spruce (*P. mariana*). Vegetation is more homogeneous in the southern half of the basin and is dominated by sedges

(*C. utriculata*) interspersed with willow. Lodgepole pine (*Pinus contorta*), white spruce, trembling aspen (*Populus tremuloides*), balsam poplar (*P. balsamifera*), and Douglas fir (*Pseudotsuga menzeisei*) are found on the surrounding hillslopes. Plant nomenclature follows Johnson et al. (1995).

The thesis research was carried out along a 360 m reach of Bateman Creek (Figs. 3.1, 3.2, and 3.3). Three sites along the reach were instrumented; two were dammed (sites A and B) and one was un-dammed (site C) (Fig. 3.2). Channel width along the reach ranges between 1.2 and 3.0 m and the gradient of the stream is 0.005 m/m (Fig. 3.3). Peat averages ~1.3 m deep in the riparian area with lenses of clay, sand, and gravel throughout. It is underlain by reduced light grey to dark grey clay (Appendix A). Beaver were active along the reach during the study and built a number of small dams that extended the width of the channel. Three beaver families inhabited the entire valley during the study period, but likely only one family was involved in dam construction and maintenance within the study reach. The study reach was flooded by a large beaver dam sometime between 1978 and 1983, and were drained sometime between 1993 and 1995, as observed on historic aerial photographs. During the study period there were three dams within the study reach: the North dam, the Hoover dam, and the Libby dam. The oldest dam (built sometime between 1995 and 2001) was the North dam, which was 0.8 m tall and 1.4 m wide. This dam had a significant amount of mineral sediment accumulated upstream and was located within site A. The Hoover dam was built on 11 July, 2007, was 0.7 m tall and 3.2 m wide, and was located ~23 m upstream of site B. This site was un-dammed in previous work carried out in 2006 (Janzen 2008), but it became a dammed site after beaver built the Hoover dam partway through the summer of 2007. The Libby dam was built on 27 July, 2008, and was 1.4 m tall and 3.0 m wide. It was located ~150 m downstream of site B and ~150 m upstream of site C (Figs. 3.1 and 3.2). All dams were constructed out of willow stems and mud. In-stream beaver dams are defined in this thesis as dams that impede stream flow, raise the water level upstream and lower the water level downstream, but allow all stream water to remain in the confines of the stream banks. The North dam was an in-stream beaver dam whereas the Hoover and Libby dams created small ponded areas in the adjacent riparian area. The dams remained in good repair during the study period as they were constantly maintained by the beaver.

Two distributaries exist around site A (Fig. 3.2). One distributary exits the west side of the main channel ~20 m upstream and re-joins the channel ~3 m downstream of site A. It developed sometime between 1995 and 2001. The west distributary is ~1 m wide, ~0.75 m deep, and water only flows through when stage is high in the main channel (C. Westbrook, personal observation). The second distributary exits the east side of the main channel ~1 m upstream and re-joins the channel ~15 m downstream of site A. It is ~0.5 m wide and has been cut down ~0.5 m. The east distributary developed in late 2007 as a result of high stream stage upstream of the North dam.

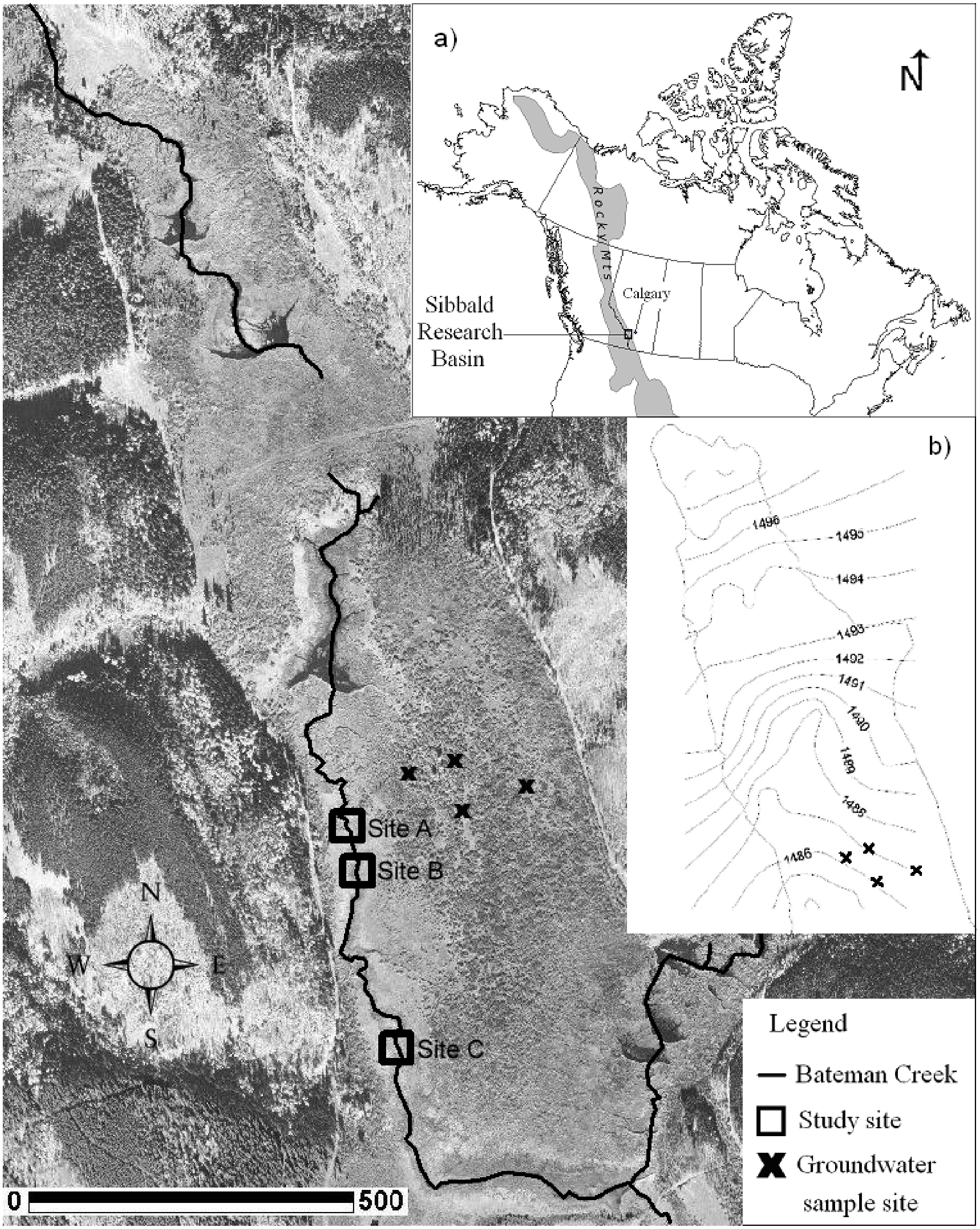

Figure 3.1. The location of Sibbald Research Basin in the Canadian Rocky Mountains (inset (a)), and a 2001 aerial photograph of the basin showing the three study reaches along Bateman Creek. Locations of groundwater sample sites are also shown. Inset (b) shows the general groundwater flow nets of the valley.

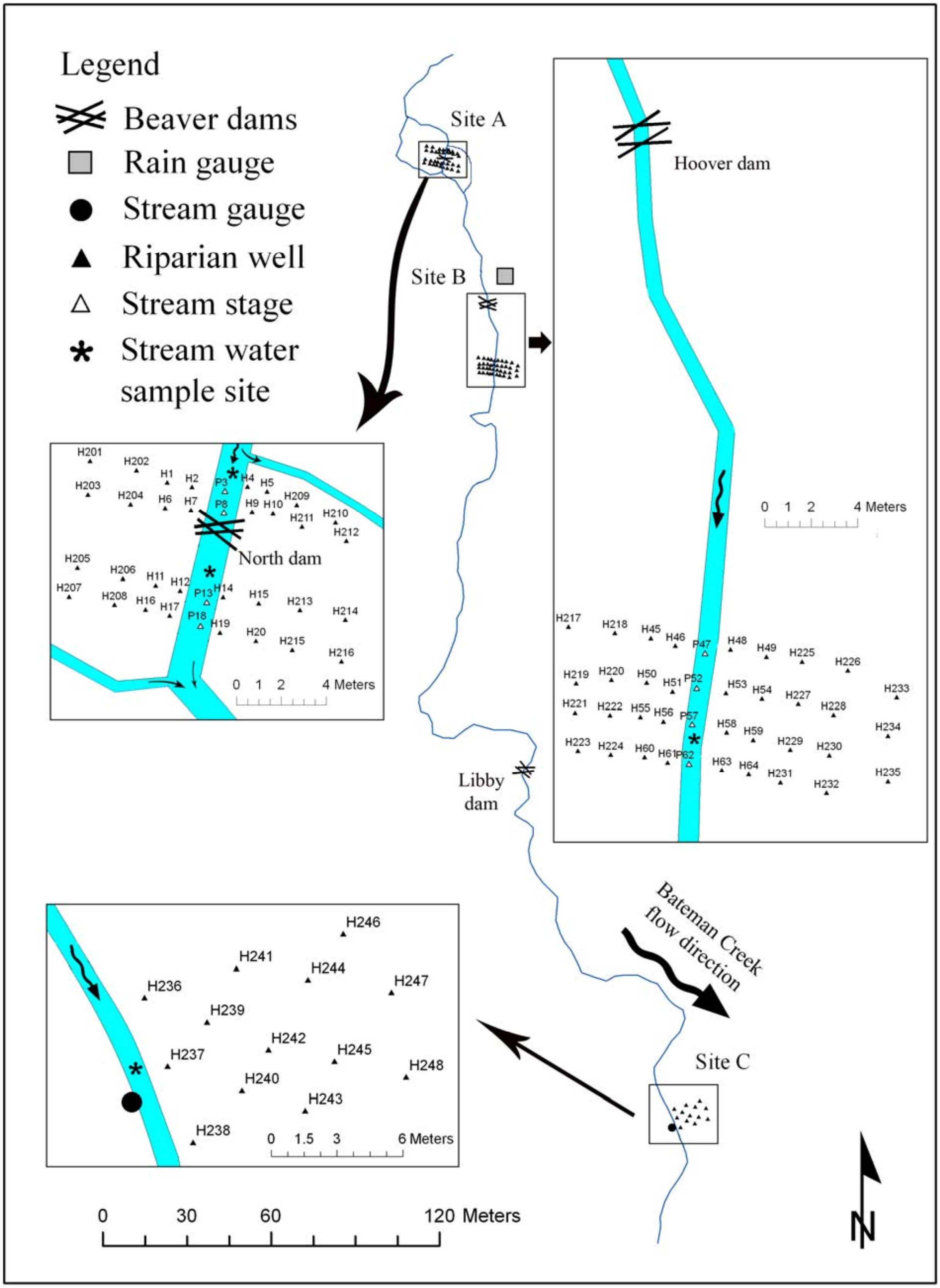

Figure 3.2. The study reach showing the location of beaver dams, riparian wells, stream stage measurements, and the automated rain (TB3 tipping bucket and standard rain gauge) and stream (OTT Thalimedes Shaft Encoder Level Sensor and float) gauges.

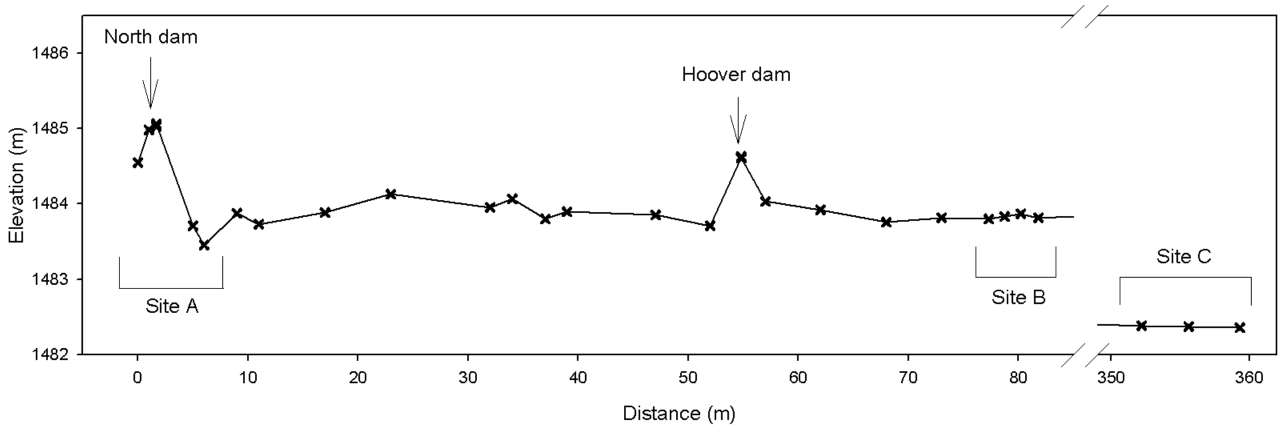

Figure 3.3. Longitudinal profile of Bateman Creek showing the location of the North dam, the Hoover dam, stream stage measurements (**x**), and study sites.

3.2 Methods

3.2.1 Stream discharge and rainfall

Manual stream gauging was carried out twice a week using a Marsh-McBirney Flo-mate 2000 velocity meter and wading rod. This was done at the stream gauge site (Fig. 3.2), where the stream flow was not impeded by beaver dams. Velocity at 60% depth was measured at 20 cm intervals across the stream channel, so that no more than 20% of the total stream velocity was measured at each point. Discharge was calculated as the product of velocity and average stream depth at each 20 cm interval. Discharge of each 20 cm interval was summed to give total discharge for the stream. Throughout the field season stream stage was measured at 15 minute intervals by an OTT Thalimedes Shaft Encoder Level Sensor and float (Fig. 3.2). Rating curves (Appendix B) were created to determine the relationship between stream discharge (Q_S) and stage from the Thalimedes. Bankfull stage was 0.85 m, and a linear regression line was used to estimate Q_S for stages >0.85 m. A significant change in channel morphology occurred at 0.3 m above the stream bed (Appendix B), so for stages <0.3 m, a power regression line was used to estimate Q_S. For stages between 0.3 and 0.85 m, a linear regression line was used to estimate Q_S.

3.2.2 Hyporheic flow

A total of 80 water table wells were installed in the east and west riparian area along the study reach (Fig. 3.2). Wells were not installed in the west riparian area at site C because a tributary coming from the west hillslope was presumed to affect groundwater flow patterns. The wells were made of 6.4 cm diameter polyvinyl chloride (PVC) pipe, slotted along their entire length, capped at the bottom, and installed by hand with a soil auger to a depth of 135 cm below ground. Soil stratigraphy was recorded for each well hole at the time of installation. The location and elevation of all wells were surveyed using a total station. The channel banks, beaver dams, streambed profile, and remaining instrumentation along the entire study reach were also surveyed.

Saturated hydraulic conductivities, K, for soils surrounding each well were estimated by performing falling head tests on each riparian well located nearest to the stream. This was done by rapidly pouring water into the wells and monitoring the drop in head over time using either a PT2X pressure transducer (Northwest Instrumentation, Oregon) for relatively rapid drops in head (i.e. minutes to hours), or manually (method described below) for wells with longer recovery times (i.e. days). Estimates of hydraulic conductivities were calculated using the Hvorslev method outlined in Freeze and Cherry (1979),

$$K = \frac{r^2 \ln(L/R)}{2LT_0} \tag{4.1}$$

where r (m) is the well radius, R (m) is the radius of the well screen, L (m) is the length of the well screen, and T_0 (s) is the time at which normalized head of 0.368 is obtained.

Water levels were measured manually using an ohmmeter that was wired to a length of graded cable that allowed an electric current to pass when the open end of the cable encountered water (Westbrook et al. 2006). This was done in all riparian wells on a weekly basis from 17 June to 28 August in 2008 (Fig. 3.2). Hydraulic heads were computed for each well, relative to sea level. Groundwater flow nets were developed for each site and date by spatial interpolation of point heads measured for the riparian wells using Surfer version 8 (Golden Software).

Stream water, groundwater, and riparian well water samples were obtained following head measurements. Stream samples (Fig. 3.2) were collected at approximately one half depth of the water. Groundwater samples were drawn from nearby standpipes (Fig. 3.1) where valley-scale groundwater flow nets show flow coming from the hillslope (Fig. 3.1b), suggesting the stream had little effect on the groundwater chemistry at these locations. Groundwater and riparian water were sampled from the standpipes using a foot valve (Solinst, Ontario) attached to a length of Tygon tubing. The wells were completely purged prior to sample collection. All water samples were collected in clean 120 mL polypropylene sample bottles and were stored on ice in the field. An aliquot from each well was analyzed for Cl^- concentration using an Orion 9617BNWP Cl^- ion activity electrode at the University of Calgary Biogeoscience Institute Laboratory. A standard curve (Appendix C) was developed by measuring the voltage (mV) for triplicates of several known Cl^- concentrations and fitting a line of best fit to data. Standards were diluted from a 1 mg/mL ±0.01 mg/mL sodium chloride stock solution (VWR, Edmonton). The equation of the standard curve was used to calculate the Cl^- concentrations of the water samples from the mV values measured by the Cl^- electrode.

The lateral extent of the hyporheic zone was delineated by examining spatial patterns in the percent stream water (%SW) of riparian wells determined using a two-component chemical mixing model. The vertical hyporheic zone was not examined because it was found to be quite shallow in this stream (Janzen 2008). In the mixing model, Cl^- concentrations of stream water, groundwater, and riparian well water were used to estimate the %SW in the riparian wells,

$$\%SW = \frac{(C_R - C_G)}{(C_S - C_G)} * 100 \tag{3.2}$$

where C_S, C_G, and C_R are the Cl^- concentrations of stream water, groundwater, and riparian well water, respectively. This method assumes that water in the hyporheic zone originates from two sources, stream water and groundwater, and that each source has a significantly different Cl^- concentration (Sklash 1990; Hill and Lymburner 1998). A paired sample *t*-test (Fig. 3.4) confirmed that there was a significant difference between stream and groundwater ($p = 0.0002$).

Riparian wells were subsequently grouped into three classes based on their %SW. Samples containing 0-20% stream water were classified as groundwater (GW), 20-80% stream water were classified as hyporheic water (HW), and 80-100% stream water were classified as stream water (SW). This classification method was modified from Triska et al. (1989) who used 10-98% stream water to classify the hyporheic zone. The delineation used in this thesis is conservative because the differences between stream and groundwater Cl^- concentrations were relatively small. The frequency of riparian wells in each class was evaluated over the study period to identify any temporal trends in the extent of the hyporheic zone.

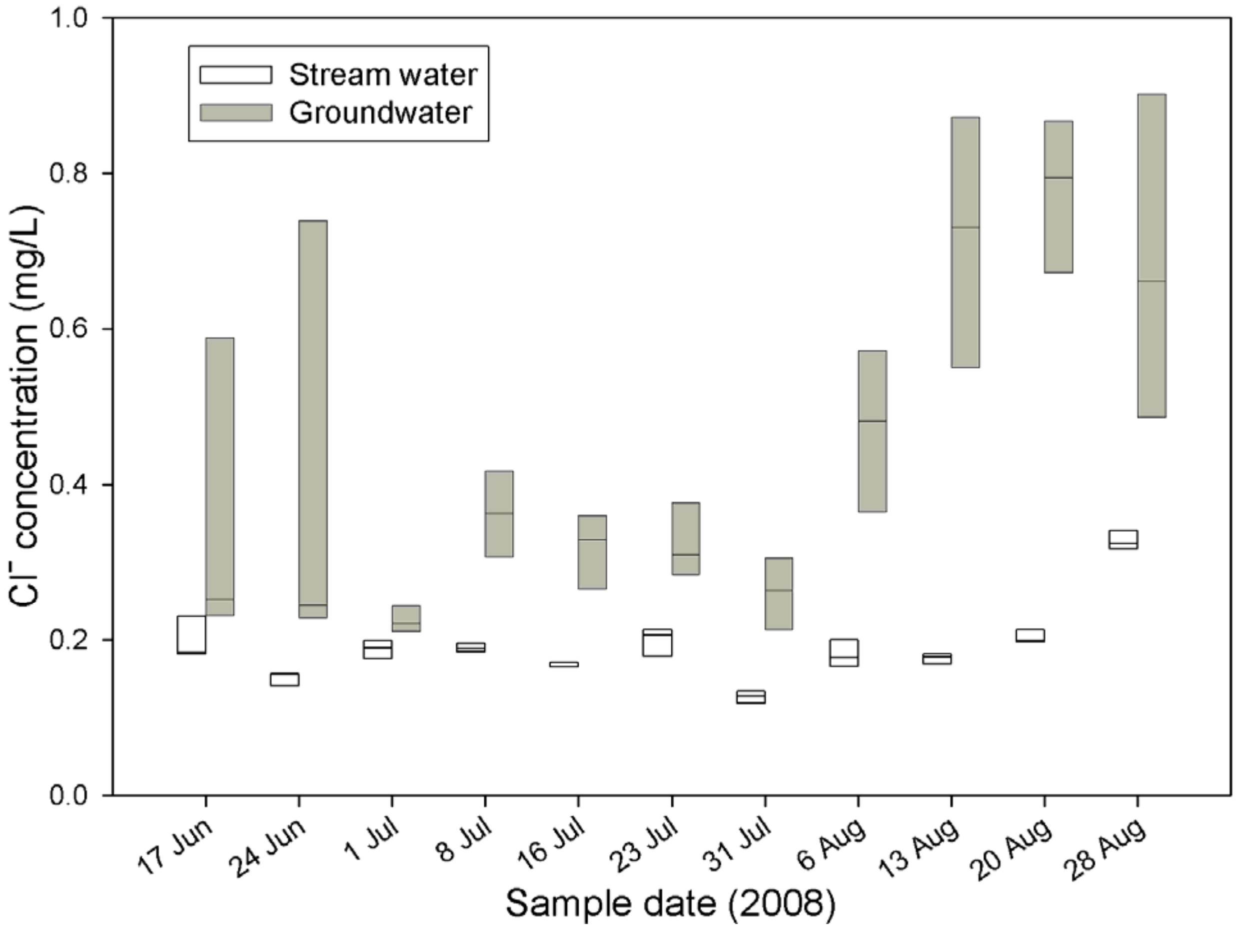

Figure 3.4. Significantly different Cl^- concentrations of stream and groundwater (paired *t*-test; $p = 0.0002$) indicate the suitability of these two end members for use in the two-component mixing model (Eqn. 3.2).

3.2.3 Hyporheic zone N and DOC availability

Riparian well samples were filtered through Whatman Grade GF/C (0.7 um) glass microfiber filter papers within 12 hours of sampling. The filtrate was immediately frozen (<-20 ºC) in 20 mL polypropylene vials until they were analyzed for dissolved N. Samples taken on 17 June, 24 June, 23 July, 31 July, and 20 August in 2008 were thawed and analyzed at the University of Saskatchewan Soil Science Laboratory for dissolved inorganic nitrogen (DIN) content (i.e. NO_3^- and NH_4^+) colormetrically with a SmartChem automated flow system autoanalyzer. TN concentrations were analyzed at the University of Saskatchewan Soil Science

Laboratory using a Shimadzu TOC-V_{CPN} analyzer. DON concentrations were calculated as the difference between the concentrations of TN and DIN. Samples from three dates were also analyzed for DOC concentrations at either the Saskatchewan Research Council Laboratory (31 July) using a Shimadzu TOC 5050A analyzer or at the University of Saskatchewan Soil Science Laboratory (24 June and 20 August) using a Shimadzu TOC-V_{CPN} analyzer. Insufficient sample volumes were available for DOC analysis on 17 June and 23 July.

Descriptive statistics were computed for each date for each N form and DOC in each riparian well class. Tests for normality revealed that several data sets had non-normal distributions even after logarithmic transformation. Hence, the nonparametric statistic Kruskal-Wallace test was used to test for differences in median N (NH_4^+, NO_3^-, or DON) or DOC concentrations between riparian well classes. Significantly different groups were identified using Dunn's multiple comparisons test. Dunn's test is a Tukey-like multiple comparisons test for ranked data with unequal sample sizes (Wheater and Cook 2000). The Kruskal-Wallace test requires an $n \geq 3$ for each class. On 20 August 2008, the stream water class contained only one riparian well, so a Mann-Whitney U test was used to test for differences between the two groups. Non-parametric correlations (Spearman rank correlation coefficients) were carried out to determine if there were statistical relationships between %SW and concentrations of NH_4^+, NO_3^-, DON, and DOC over the entire study period. Correlations were also carried out for DOC and DON concentrations to determine if they were related. All statistical analyses were done manually or using SPSS version 14.0 (LEAD Technologies, Inc).

Hot spots of N and DOC availability were determined for the riparian wells for each sampling date by identifying outliers that were greater than 1.5 interquartile ranges (IQR) from the 75th percentile (Harms and Grimm 2008). In contrast, cold spots were determined by identifying data points that were less than the 10^{th} percentile. Hot and cold spots were displayed on maps and compared to the flow nets and beaver dam locations to assess spatial patterns.

3.2.4 Potential water, N, and DOC fluxes

Lateral fluxes of water, Q_{flux} (m^3/s), between the riparian area and the stream were calculated using Darcy's equation,

$$Q_{flux} = -KA\frac{(h_S - h_R)}{\Delta l} \tag{3.3}$$

where h_S-h_R is the difference between the stream stage at the thalwag and the hydraulic head in the nearest riparian well (m), K is the hydraulic conductivity of the riparian well (m/s) (Appendix D), Δl is the lateral distance between the riparian well and the stream thalwag (m), and A is the representative unit area of the stream bank (m^2) normal to the direction of flow (Fig. 3.5). Negative values of Q_{flux} indicate that water is moving from the stream to the riparian area.

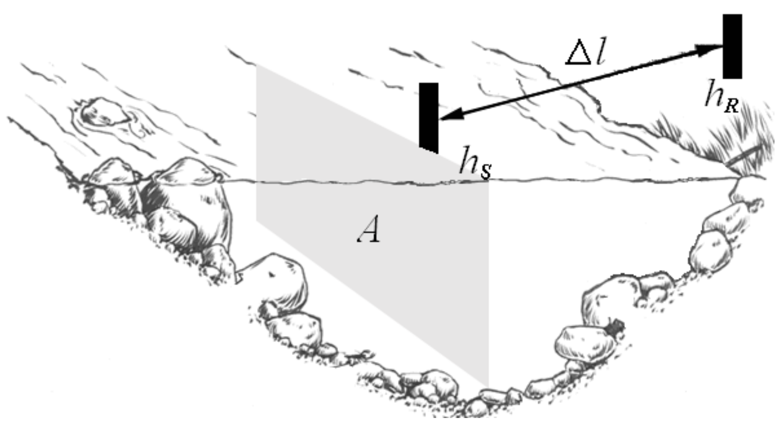

Figure 3.5. Cross-section of stream identifying the variables involved in calculating the water flux between the stream and riparian area. Variables are used in Darcy's equation (Eqn. 3.3) and are defined above. Black rectangles are standpipes (modified from Missouri Department of Conservation).

Potential lateral N and DOC fluxes across the stream-hyporheic interface, N_{flux} (mg/day), were calculated by,

$$N_{flux} = Q_{flux} C \quad (3.4)$$

where C is the concentration of N (NH_4^+, NO_3^-, or DON) or DOC (mg/L) in the stream or riparian well depending on the direction of water flux (Q_{flux} in L/day). Mean summer fluxes were calculated for each site, and upstream and downstream of the North dam.

CHAPTER 4 – RESULTS

4.1 Stream and riparian hydrology

4.1.1 Stream discharge and rainfall

Rainfall events were frequent and large in early summer 2008. A total of 271 mm of rain fell in the basin during three large spring rain events (Fig. 4.1); 150 mm and 100 mm of rain fell during the first (21 to 26 May) and third (7 to 11 June) storms, respectively, resulting in rapid increases in Q_S, overbank flooding at the stream gauge, and subsequent loss of discharge data. The second event (21 mm, 1 to 4 June) also resulted in a sizable increase in Q_S, but the stream stage gauge remained intact. Following the large rainfall events in May and June, discharge receded until it reached baseflow conditions in late July (Fig. 4.1). Rain events were smaller (typically <15 mm) during the sampling period (17 June to 28 August), with a total of 158 mm of rain falling in the valley during this time. Q_S was responsive to small rainfall events (i.e. >10 mm) throughout the summer.

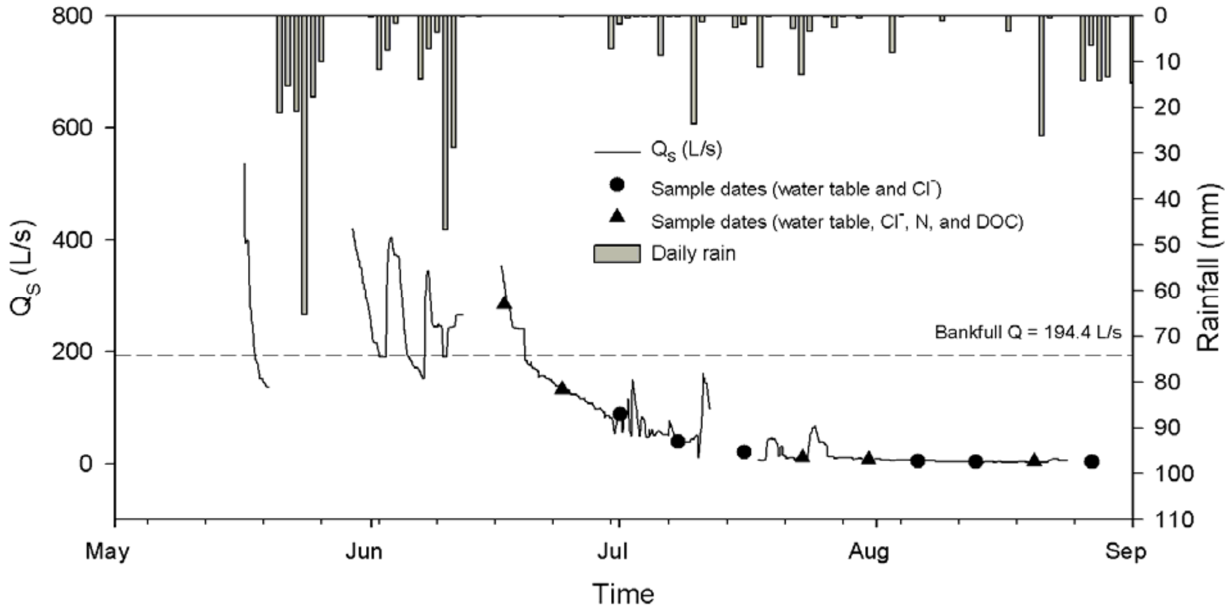

Figure 4.1. Bateman Creek hydrograph (hourly discharge) and hyetograph (daily rain) for summer 2008. Water quality sampling dates are plotted on the hydrograph.

4.1.2 Groundwater flow nets

The flow nets show a looping pattern of groundwater flow around the dam at site A (Fig. 4.2). Stream water was directed into the east and west riparian areas upstream of the North dam and directed back to the stream downstream of the dam. This pattern persisted throughout the study, including dates not shown in Fig. 4.2. Hydraulic gradients along the main flow paths decreased throughout the summer from 0.08-0.09 m/m on 17 June to 0.05-0.06 m/m on 20 August as the water table in the riparian area declined.

Groundwater flow at site B was generally directed from the east and west riparian area toward the stream between 17 June and 23 July. Hydraulic gradients ranged from 0.03-0.06 m/m during this time. There were also short and opposing flow paths at the stream-riparian boundary that resulted in a convergence of water 10 to 20 cm into the riparian area, but the dominant flow pattern was toward the stream. On 31 July, immediately following the construction of the Libby dam, hydraulic gradients reversed on both the east and west sides (-0.03 m/m) of the stream such that stream water was directed a few meters into the riparian area. Groundwater flow remained directed to the stream (hydraulic gradients of 0.03-0.06 m/m) further out in the riparian area, resulting in a convergence of flow paths 2.5 m west of the stream and 3.5 m east of the stream. The same type of flow system was observed west of the stream on 20 August. East of the stream, the flow system was different such that stream water was directed much further (at least 7.5 m) into the riparian area. The hydraulic gradient across the east riparian area was -0.05 m/m.

At site C, groundwater flow patterns and hydraulic gradients varied little throughout the study. Two main flow paths were observed; one wherein stream water was directed toward the riparian area and a second wherein riparian water was directed toward the stream. The opposing flow paths resulted in a convergence of groundwater 0.75-2.25 m into the riparian area, depending on the date. Hydraulic gradients directed toward the stream were smaller on 20 August (0.06 m/m) compared to those measured on 23 July and 31 July (both were 0.10 m/m). Similarly, hydraulic gradients directed toward the riparian area were smaller on 20 August (0.11 m/m) compared to those measured on 23 July and 31 July (both were 0.16 m/m).

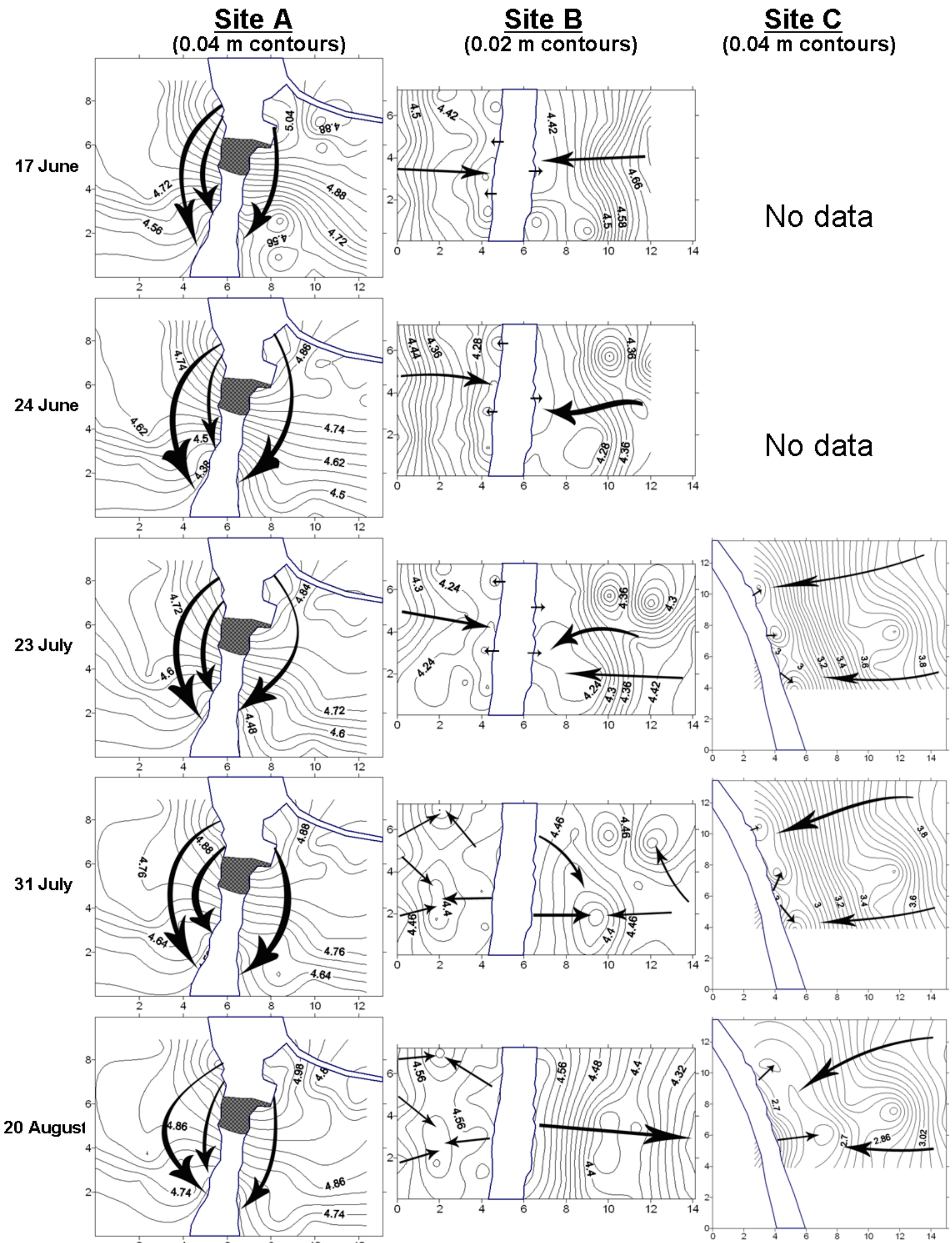

Figure 4.2. Groundwater flow nets for each site on five sampling days derived from kriging point head measurements. Contours are lines of equipotential and black arrows show general flow direction.

4.1.3 Hyporheic zone delineation

The frequency of riparian wells classed as SW, HW, or GW changed throughout the study period (Fig. 4.3). The proportion of riparian wells classed as GW decreased from 39% to 13% between 17 June and 16 July, increased to 39% on 23 July, and then decreased to <5% in August. The proportion of riparian wells classed as SW slightly increased from 27% to 35% between 17 June and 16 July, decreased to 15% on 31 July, and then increased to 63 to 85% in August. The proportion of riparian wells classed as HW fluctuated between 25 and 50% on most sample days, but reached as high as 60% on 31 July and as low as 13% on 28 August. Throughout August, 95% of riparian wells were classed as either SW or HW. The location of wells within each riparian well class (Fig. 4.4) was consistent with the main flow paths depicted on the groundwater flow nets (Fig. 4.2). Nearly all riparian wells located upstream of the North dam where stream water was forced into the riparian area by the dam were classed as SW and HW. Riparian wells located below the dam where water was directed back toward the stream were mainly classed as GW. Following the construction of Libby dam (31 July and 20 August sample dates), almost all of the riparian wells downstream of the North dam were classed as SW or HW.

There was a high frequency of riparian wells classed as GW near the stream at site B on most dates. Many of the wells located further out in the riparian area were classed as either SW or HW even though the flow nets show riparian water is directed toward the stream in these locations (Fig. 4.2). On 20 August almost all of the riparian wells at site B were classed as SW or HW.

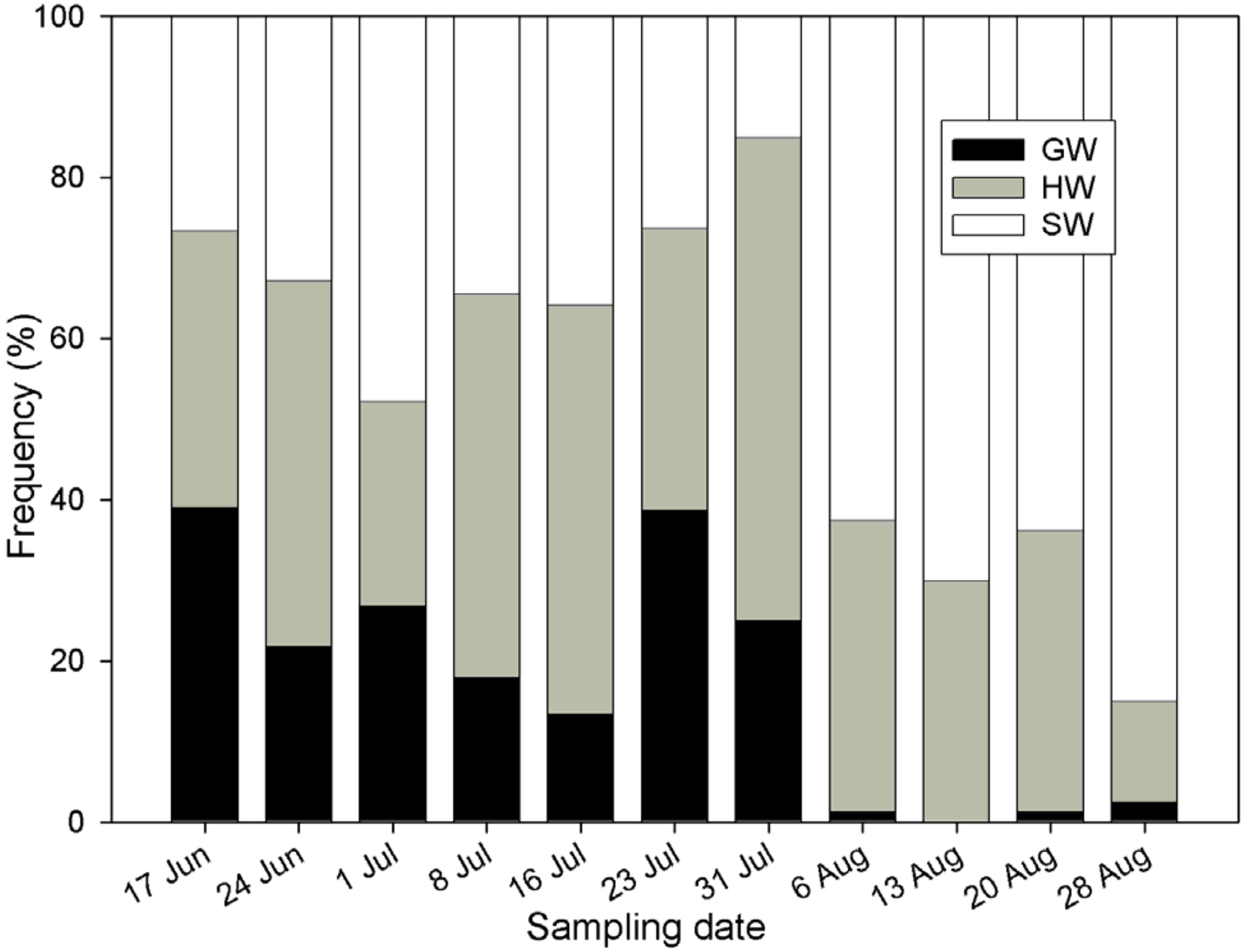

Figure 4.3. Bar graph showing the percentage of riparian wells classed as groundwater (GW), hyporheic water (HW), and stream water (SW) using a two-component mixing model throughout the summer of 2008.

Site C was the most variable in terms of location of riparian well classes within the riparian zone. Some riparian wells near the stream (75 cm into the riparian area) were classed as GW on two of the sample dates (23 July and 31 July). However, there were wells classed as SW and HW further out in the riparian area, despite that the groundwater flow nets showed water flowing to the stream. On 20 August, riparian wells were classed as either SW or HW throughout the site.

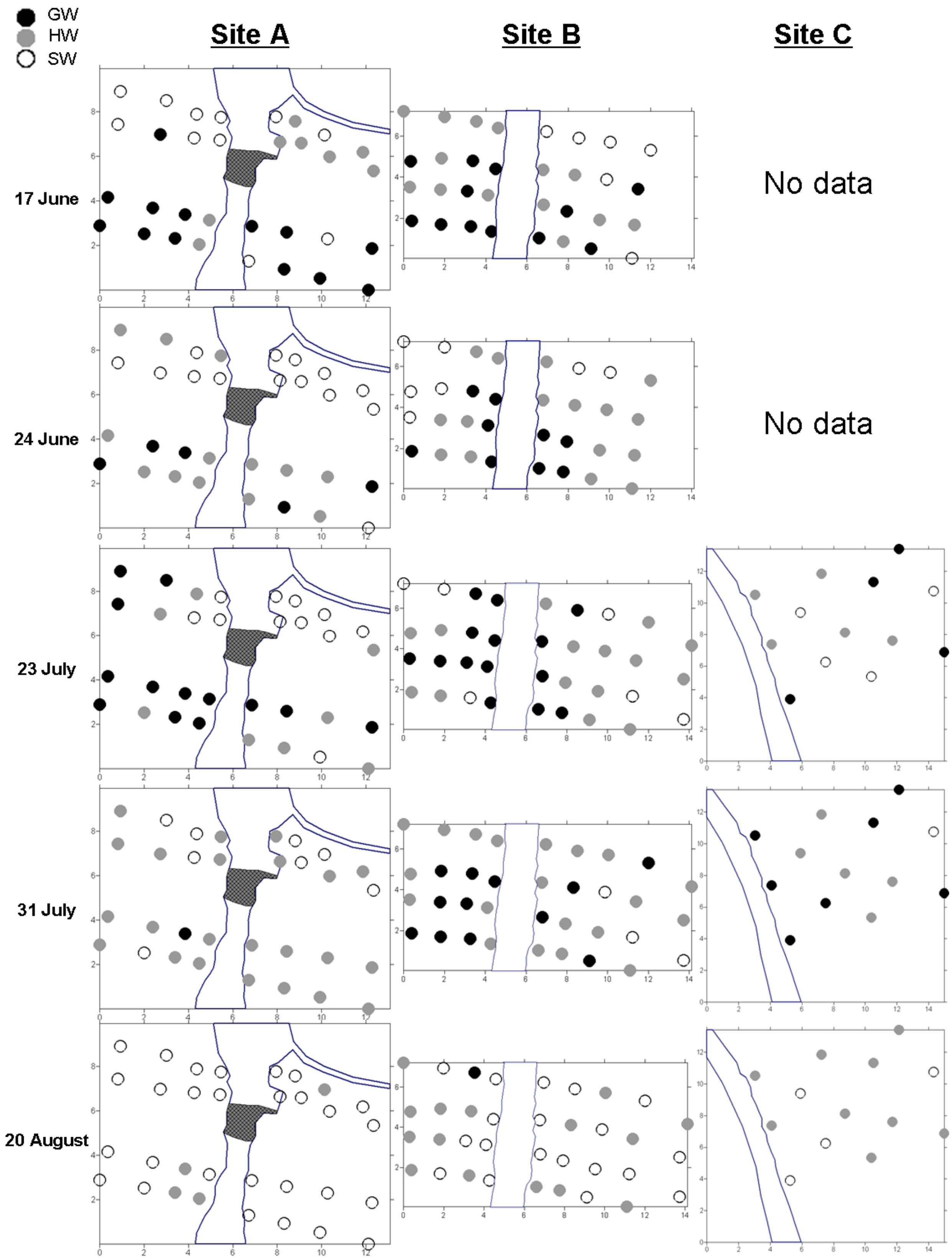

Figure 4.4. Riparian well classes, groundwater (GW), hyporheic water (HW), and stream water (SW), displayed spatially for five sample dates in 2008 at the three sites.

4.2 N dynamics in relation to stream-aquifer mixing

4.2.1 Stream and groundwater chemistry

Concentrations of NH_4^+, NO_3^-, and DON in stream water were relatively low throughout the study period (Fig. 4.5a), and varied little with changes in stream stage over time (Fig.4.5c). More variability was observed in groundwater N concentrations over time (Fig. 4.5b). Although groundwater NO_3^- concentrations were low and relatively constant throughout the study period, DON peaked on 31 July, and NH_4^+ increased five-fold throughout late July and August. Groundwater tables showed an overall decline during the study period by up to 60 cm (Fig. 4.5d).

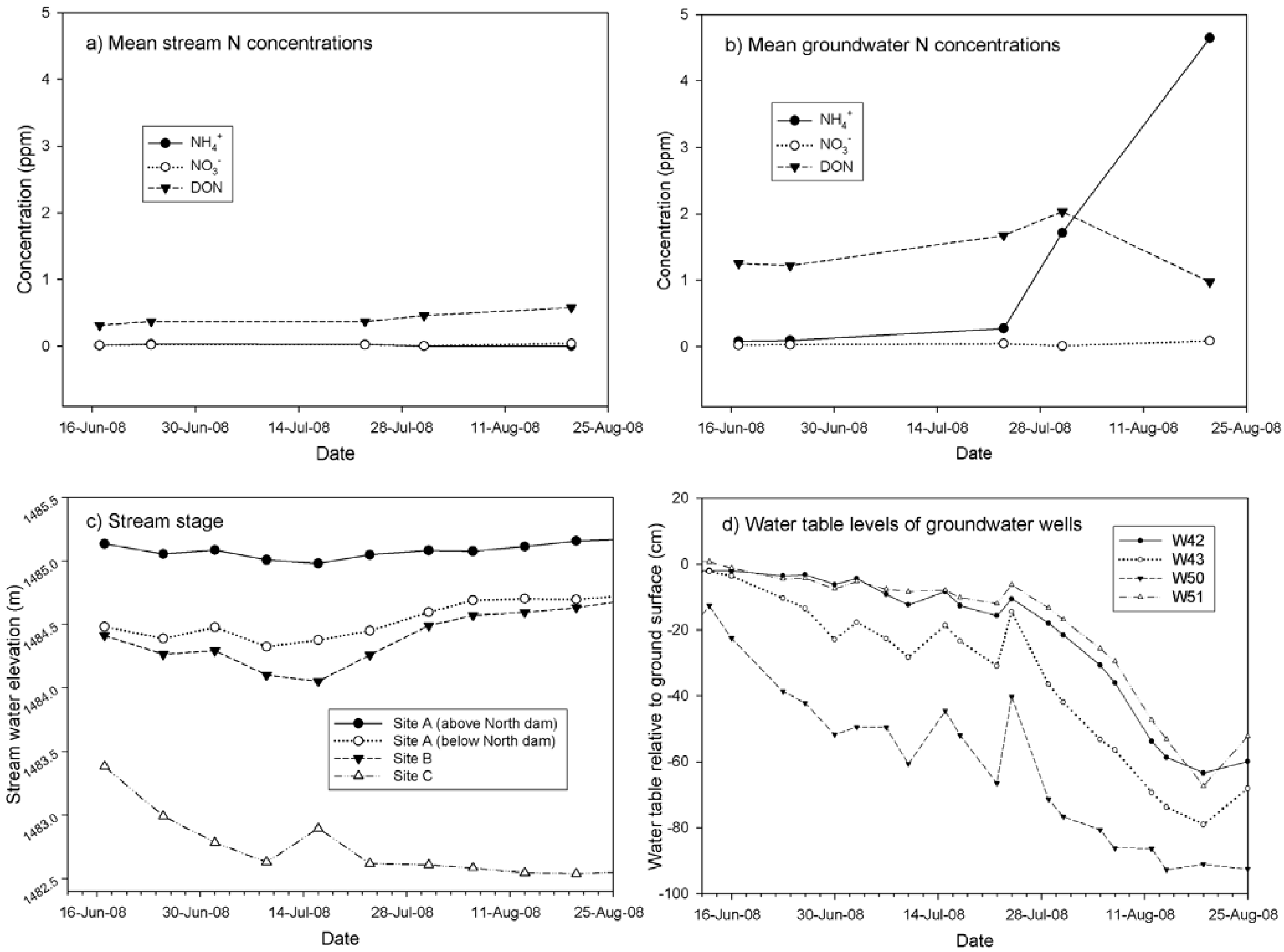

Figure 4.5. Mean N concentrations (n=4) of stream (a) and groundwater (b) for five sample dates in 2008. Temporal variations in (c) stream stage and (d) water table levels at groundwater sampling sites are also displayed.

4.2.2 Riparian well chemistry

There were significant differences in NH_4^+ concentrations between riparian well classes for all sampling dates (Table 4.1). On 17 June, 24 June, 23 July, and 20 August riparian wells classed as SW had significantly lower NH_4^+ concentrations than GW and HW classed wells, but there was no difference between GW and HW classed wells. On 31 July, GW classed wells had significantly higher NH_4^+ concentrations than SW and HW, but there was no significant difference between SW and HW classed wells. No significant differences were found in NO_3^-, DON, or DOC concentrations among riparian well classes for any of the sample dates except 24 June. On that day DOC concentrations for GW classed wells were significantly higher than for SW classed wells, but neither GW nor SW were different from HW.

Significant correlations were found between %SW in the riparian wells and concentrations of some N forms: %SW was significantly correlated with concentrations of NH_4^+ (r_s=-0.479; p=0.000) and NO_3^- (r_s=0.143; p=0.006), but not with concentrations of DON (r_s=0.027; p=0.607) or DOC (r_s=-0.119; p=0.079). There was also a significant positive correlation found between DON and DOC concentrations (r_s=0.407; p=0.000).

Table 4.1. Comparison of NH_4^+, NO_3^+, DON, and DOC concentrations among riparian well classes. The Kruskal-Wallace (n≥3) and Mann-Whitney (n<3) tests were used to test for statistical differences between riparian well classes. Dunn's multiple comparisons test was used to determine which groups were different. Class median and coefficient of variation (CV) are reported. Riparian well classes with the same letter are not significantly different (α=0.05).

Sample Date	Riparian well class†	n	NH_4^+ (mg/L) Median	CV	NO_3^- (ug/L) Median	CV	DON (mg/L) Median	CV	DOC (mg/L) Median	CV
17 Jun	GW	25	^{a}0.547	1.395	^{a}17.00	0.659	^{a}0.631	0.559		
	HW	22	^{a}0.380	1.267	^{a}17.00	0.512	^{a}0.588	0.588	No data	
	SW	17	^{b}0.051	1.267	^{a}15.00	0.594	^{a}0.462	0.570		
24 Jun	GW	14	^{a}2.549	0.977	^{a}27.00	0.493	^{a}0.446	0.830	^{a}46.90	0.275
	HW	29	^{a}0.696	1.349	^{a}13.00	0.803	^{a}0.619	0.668	^{a,b}39.51	0.269
	SW	21	^{b}0.060	1.731	^{a}12.00	1.046	^{a}0.534	0.540	^{b}28.68	0.319
23 Jul	GW	31	^{a}0.651	1.248	^{a}33.50	0.943	^{a}0.636	0.995		
	HW	28	^{a}0.358	1.434	^{a}36.00	0.447	^{a}1.106	0.489	No data	
	SW	21	^{b}0.043	2.940	^{a}33.00	0.740	^{a}0.502	0.727		
31 Jul	GW	20	^{a}2.546	0.990	^{a}9.500	0.589	^{a}1.223	0.820	^{a}27.00	0.544
	HW	48	^{b}0.523	1.331	^{a}10.00	0.652	^{a}0.797	0.674	^{a}18.50	0.620
	SW	11	^{b}0.097	1.766	^{a}13.00	0.647	^{a}0.887	0.591	^{a}13.00	0.595
20 Aug	GW	1	§6.231	NA	§17.00	NA	§0.025	NA	§38.06	NA
	HW	28	^{a}0.864	1.175	^{a}55.50	0.457	^{a}1.044	0.770	^{a}38.33	0.433
	SW	49	^{b}0.203	1.750	^{a}49.00	0.542	^{a}0.715	1.240	^{a}28.90	0.499

†, classes were derived using well Cl^- concentrations in a two-component mixing model
§, single value so cannot compare statistically with other classes

4.2.3 Hot and cold spots

There were 5 to 8 NH_4^+ cold spots at site A on each sample date (Fig. 4.6). Cold spots were concentrated upstream of the North dam where flow nets (Fig. 4.2) showed stream water exiting the stream. Cold spots of NO_3^- (Fig. 4.7) and DOC (Fig. 4.9) were coincident with NH_4^+ cold spots, and also were found downstream of the North dam along the main hyporheic flow paths. Few DON cold spots were observed throughout the study at site A (Fig. 4.8). No NH_4^+, DON, and DOC hot spots and only two NO_3^- hotspots were observed at site A throughout the study.

There were 8 to 13 NH_4^+ hot spots at site B on each sample date, which were located mainly west of the stream (Fig. 4.6). In contrast, only one NH_4^+ cold spot was observed throughout the entire study. Few NO_3^- and DON hot spots were found at site B, whereas many cold spots were found west of the stream coincident with NH_4^+ hot spots. Coincident with the NH_4^+ hot spots were NO_3^- (3 to 10) and DON (4 to 8) cold spots. One of the NO_3^- hot spots was found at site B on all dates except 23 July. There were few DON hot spots found throughout the sample period, with the greatest number (4) occurring on 20 August. There was no DOC hot or cold spots observed on any sample dates at site B.

Site C had the fewest hot and cold spots. There were ≤1 NH_4^+, 1 NO_3^-, ≤1 DON, and ≤2 DOC cold spots observed on each sample date. They were generally located near the stream. While no NH_4^+ and NO_3^- hot spots were found on any of the sample dates, 2 to 3 DON and 1 DOC hot spots were found further out in the riparian area on each sample date.

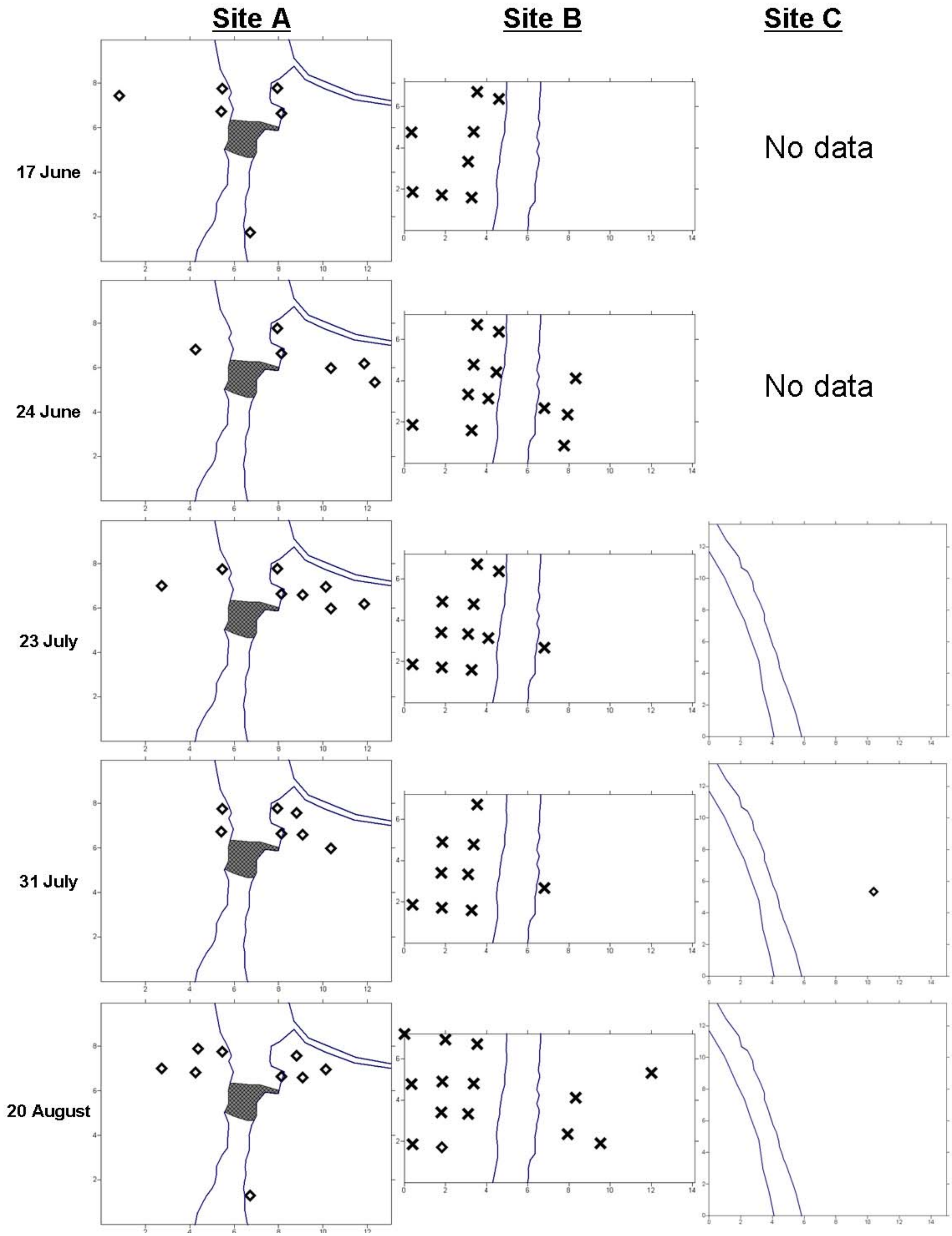

Figure 4.6. Hot (**X**) and cold spots (◊) of NH_4^+ availability displayed spatially for all sites and sample dates.

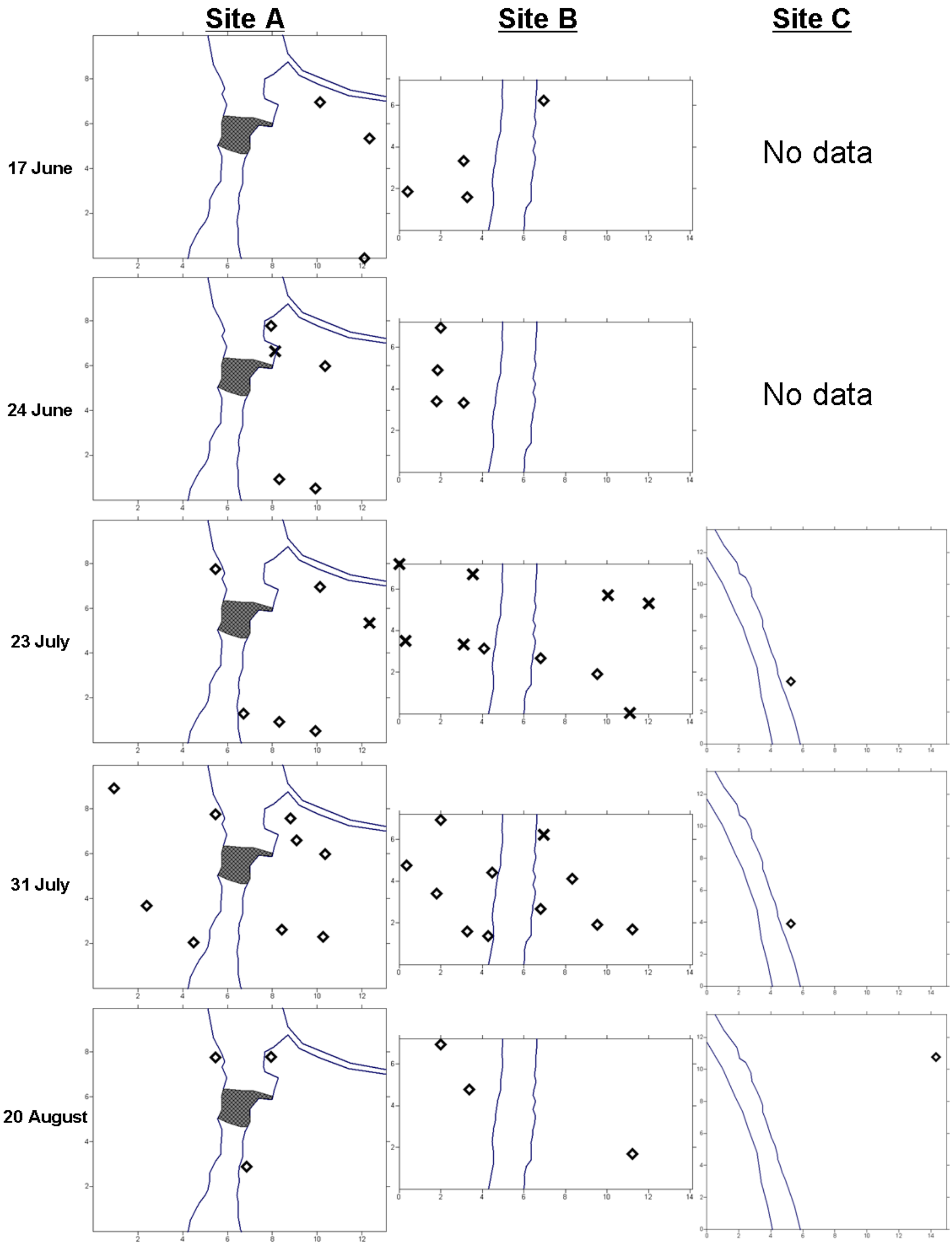

Figure 4.7. Hot (**X**) and cold spots (◊) of NO_3^- availability displayed spatially for all sites and sample dates.

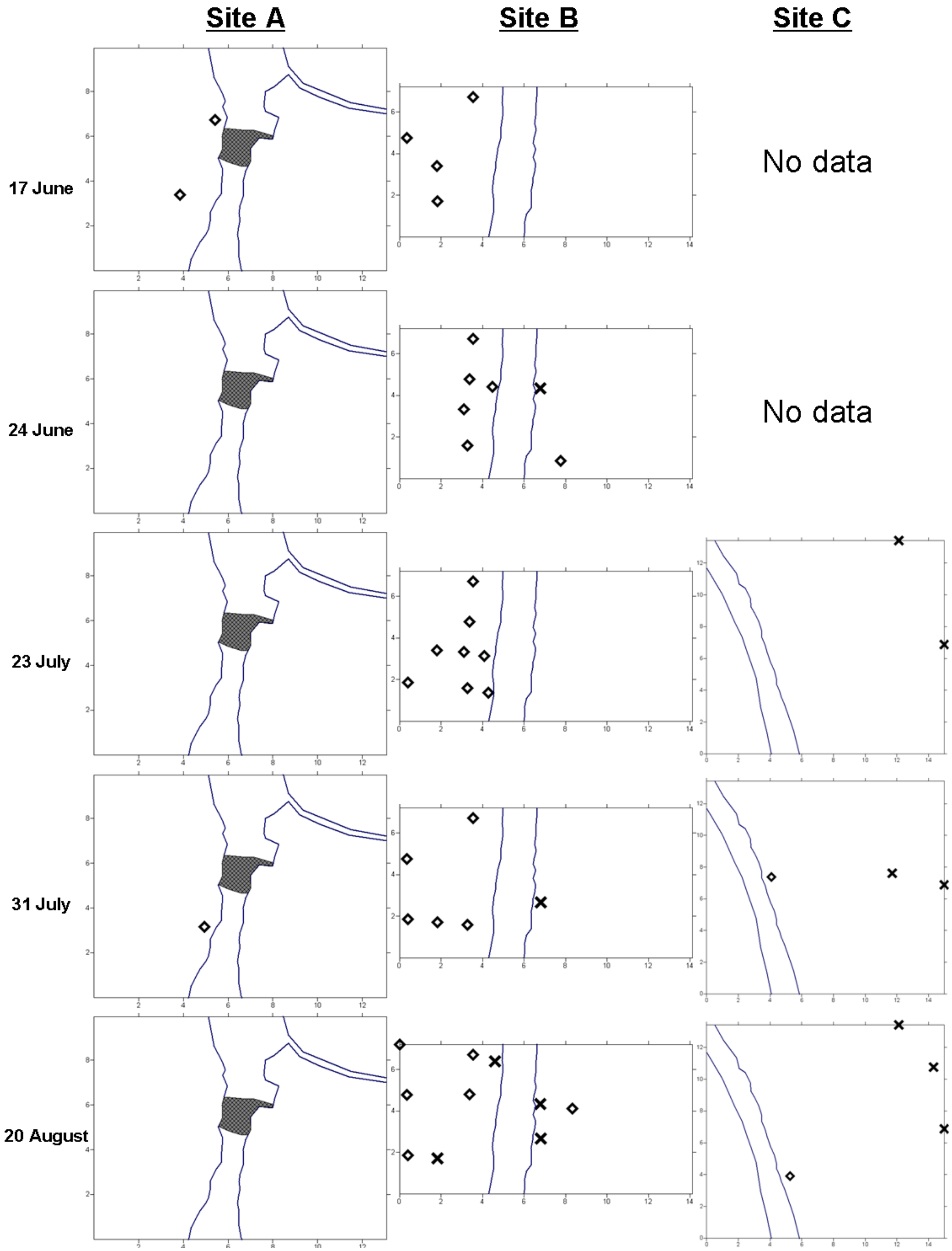

Figure 4.8. Hot (**X**) and cold spots (◊) of DON availability displayed spatially for all sites and sample dates.

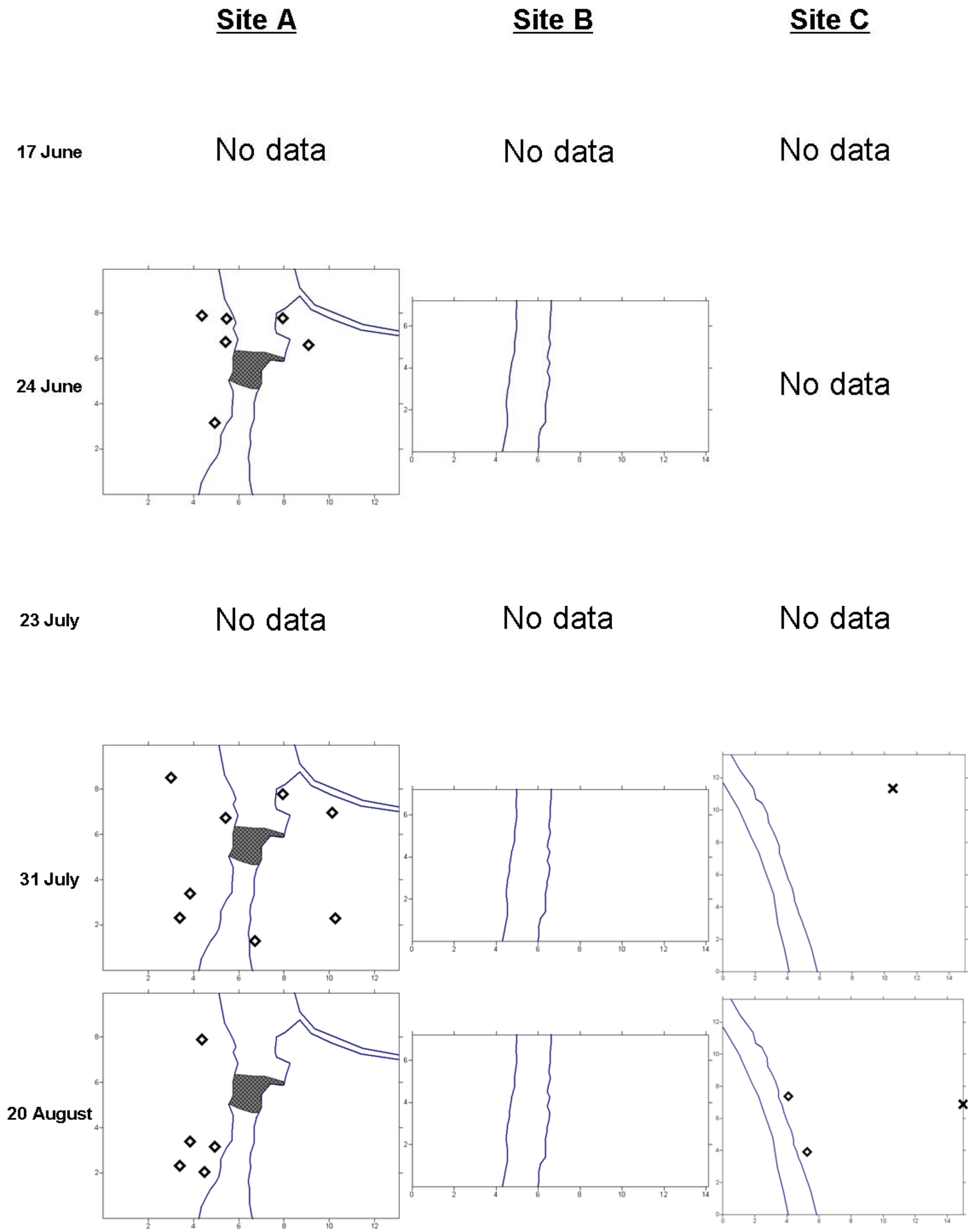

Figure 4.9. Hot (**X**) and cold spots (◊) of DOC availability displayed spatially for all sites and sample dates.

4.3 Fluxes across the stream-aquifer interface

Water fluxes (Q_{flux}) were generally small at all but site A (Fig. 4.10) where 208 L/day of water on average moved from the stream into the riparian area upstream of the North dam. Downstream of the North dam, 597 L/day moved from the riparian area to the stream resulting in a net gain of 389 L/day water to the stream at site A. The summer average Q_{flux} at site B was an order of magnitude lower (68 L/day) than at site A, and was directed from the stream to the riparian area. Water also moved from the stream to the riparian area at site C, with an average net flux of 116 L/day. Despite the net losses of water from the stream at sites B and C, there was an overall net gain of 204 L/day of water to the stream within the study sites due to the large net water flux to the stream at site A.

Potential NH_4^+ fluxes were the greatest of all N forms. There was a mean net NH_4^+ flux of 215 mg/day from the riparian area to the stream at site A (Fig. 4.10). The NH_4^+ flux of 3.0 mg/day to the riparian area upstream of the North dam was relatively small compared to the mean NH_4^+ flux of 218 mg/day toward the stream downstream of the dam. Site B had a net flux of 1.6 mg/day of NH_4^+ to the stream and site C had a net flux of 1.4 mg/day to the riparian area.

The potential NO_3^- fluxes to the riparian area upstream of the North dam was 4.6 mg/day NO_3^-, whereas 13 mg/day NO_3^- moved from the riparian area to the stream downstream of the dam (Fig. 4.10). This resulted in a net gain of 8.5 mg/day NO_3^- by the stream at site A. Potential NO_3^- fluxes at sites B and C were smaller than fluxes at site A (1.6 mg/day and 2.5 mg/day, respectively), and were directed to the riparian area.

The potential net DON flux for all sites was 95 mg/day DON from the riparian area to the stream (Fig. 4.10). This was attributed to the relatively large DON flux at site A downstream of the North dam (267 mg/day to the stream). All other sites had potential DON fluxes to the riparian area: upstream of the North dam the potential DON flux was 90 mg/day, site B was 29 mg/day, and site C was 53 mg/day.

Potential fluxes of DOC to the stream were considerably larger than N fluxes (Fig. 4.10). On average, the mean net DOC flux for all sites was 3.5 g/day directed from the riparian area to the stream. There was a potential DOC flux of 4.2 g/day to the riparian area upstream of the North dam and a potential flux of 10.6 g/day to the stream downstream of the dam. Only the section below the North dam had an average potential DOC flux to the stream; it was >2 times larger than the mean flux upstream of the North dam and >4 times larger than the mean fluxes at both site B (1.4 g/day) and site C (1.5 g/day).

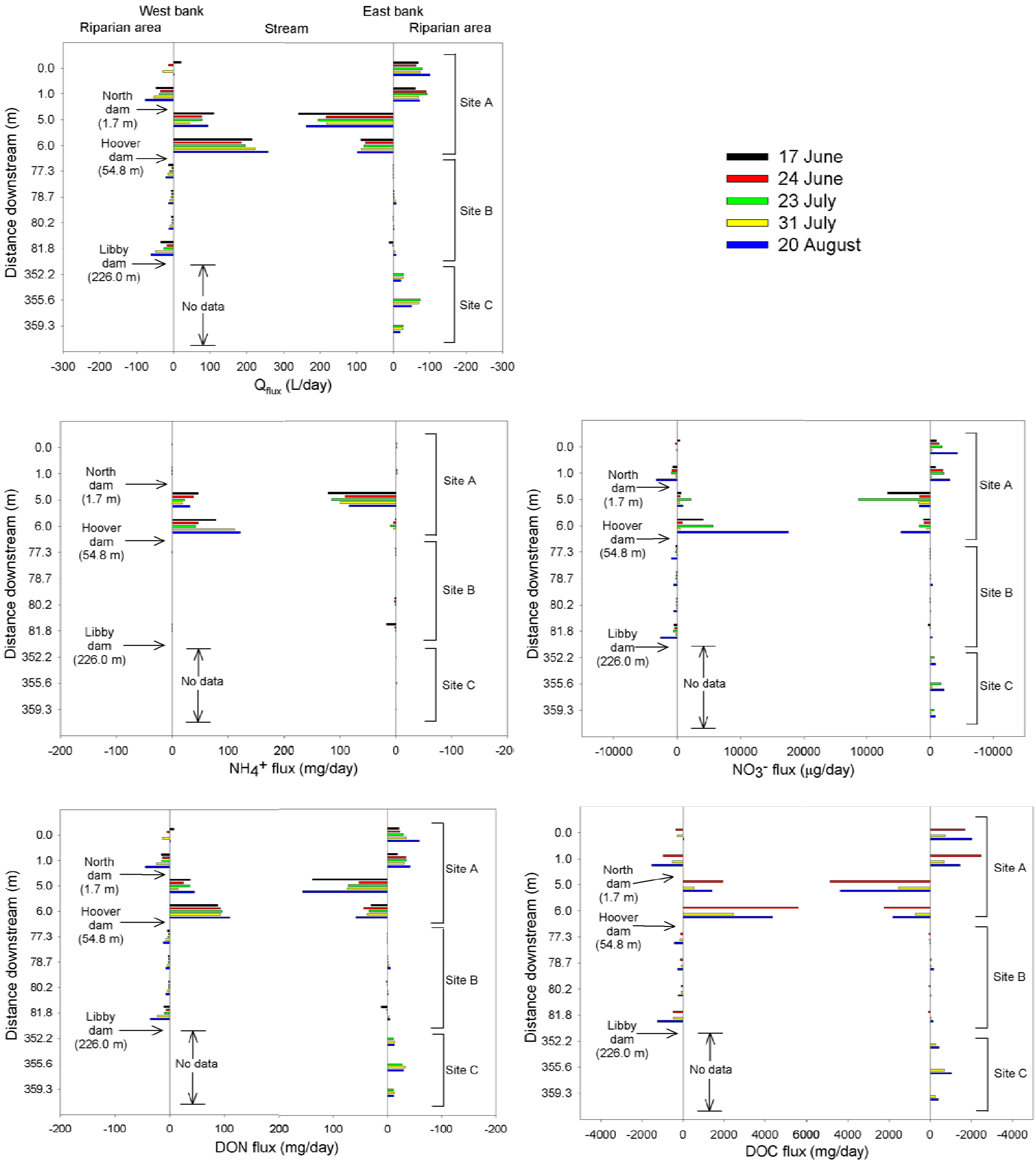

Figure 4.10. Potential fluxes of water (Q_{flux}), NH_4^+, NO_3^-, DON, and DOC between the stream and riparian area within the three study sites along Bateman Creek.

CHAPTER 5 – DISCUSSION

5.1 Extent of hyporheic exchange

The results from Cl^- concentrations used in the mixing equation suggest the extent of the hyporheic zone is usually restricted to the first set of riparian wells adjacent to the stream (i.e. 0.75 m into the riparian area) unless beaver dams are present along the stream reach. Many riparian wells near the stream at sites B and C had >80% groundwater on most dates sampled (17 June to 31 July). This limited extent of the hyporheic zone was not observed on 20 August likely because the Libby dam constantly raised stream and riparian water tables throughout August, causing flooding in some areas. As a result, very few riparian wells were classed as GW upstream of the Libby dam (sites A and B) on 20 August. The absence of a wide lateral hyporheic zone on 17 June to 31 July results from hydraulic gradients that generally opposed extensive movement of stream water into the riparian area. This has been previously demonstrated by others (e.g. Hill and Lymburner 1998) examining vertical hyporheic zones.

The small temporal variations in hyporheic zone extent that were observed along the un-dammed section of stream may be attributed to variations in Q_S. For example, Wondzell and Swanson (1996a) found that riparian water tables were higher than stream stage during high Q_S conditions, which created hydraulic gradients that opposed extensive movement of stream water into the riparian area. Such a pattern was observed at site C. Hydraulic gradients decreased slightly during August when Q_S was at baseflow conditions, which resulted in stream water and groundwater convergence several meters further out in the riparian area. Throughout June and

July, when Q_S was higher, the groundwater contribution in the riparian area was greater. This suggests that during higher Q_S, high water tables caused a hydraulic gradient that opposed extensive movement of stream water into the hyporheic zone and resulted in a 65% contraction in the hyporheic zone, whereas low baseflow conditions decreased hydraulic gradients and promoted expansion of the hyporheic zone. The observed variation in hyporheic zone extent due to fluctuations in Q_S is greater than that observed by Harvey et al. (1996) and Wondzell and Swanson (1996a). They documented a 30-50% hyporheic zone contraction at high Q_S, attributed to increased groundwater inflow that resisted recharge of stream water to hyporheic flow paths. However, in this thesis the extent of the hyporheic zone only varied by 1.5 m due to variations in Q_S.

Results from this study suggest there is a wider lateral hyporheic zone along the sections of the stream dammed by beaver. Small variations in channel geometry and morphology have been shown by others to cause variations in hyporheic zone extent (Lautz and Siegel 2006; Wondzell 2006; Greenwald et al. 2008). The old stream meander located immediately upstream of site A on the west riparian area could have caused the observed increase in hyporheic exchange near the North dam. However, this is unlikely as the same pattern of hyporheic flow was found in both the east and west riparian areas. It is more likely that the North beaver dam was driving the observed variations in hyporheic zone extent between sites. Further, the sections of stream impacted by beaver dams showed increased hyporheic exchange even during times when high Q_S opposed extensive hyporheic exchange along the study reach. Ponding of water upstream of the North dam increased head gradients between the stream and riparian area by 0.03-0.05 m/m. This promoted greater extension of stream water into the riparian area at site A upstream of the North dam. Hyporheic water flowed in a looping pattern around the dam, which has been observed in this riparian area previously (Janzen 2008) and other riparian areas adjacent to streams dammed by beaver (Lautz et al. 2006; Hill and Duval 2009). On average, 2.9 times more water returned to the stream below the North dam than left above it. By increasing the movement of water through the riparian area, and in turn, increasing the stream water extension into the riparian area even during periods of high Q_S, the influence from the dam exceeded the influence that variations in Q_S had on hyporheic zone extent.

Further evidence of enhanced hyporheic exchange due to beaver dams is the reversal of flow direction at site B following the construction of the Libby dam on 27 July. At the beginning of the summer and throughout 2006 and 2007 (Janzen 2008) the general flow direction was toward the stream at site B, but immediately following Libby dam's construction gradients were toward the riparian area and water was directed >2.5 m into the riparian area. Also, Q_{flux} was directed to the riparian area and increased by ~2.6 times after dam construction. There were no directional changes in hydraulic gradients at sites A or C at this time, suggesting that the Libby dam induced the flow reversal.

Many of the riparian wells farthest away from the stream are classed as SW and HW even though the flow nets suggest subsurface flow is toward the stream in these locations. Small and negative Q_{flux} at sites B and C shows that there is some movement of stream water into the riparian area, but the flow nets show stream water penetrates only a few meters into the riparian area. This pattern could simply be due to small differences in Cl^- concentrations between the stream and groundwater end members, which would result in a poor estimation of %SW. However, the most likely explanation for the classification of wells as SW or HW farthest away from the stream at sites B and C is that they are a part of a larger hyporheic flow system in which stream water has been forced further into the riparian area and has flowed along longer flow paths before returning to the stream. Such a hyporheic flow path could be generated by the Hoover dam and/or Libby dams, or a large beaver dam located upstream of the study reach. Since riparian wells furthest from the stream at site A were classed as GW, it is likely that the Hoover and/or Libby dams were the cause of riparian wells furthest from the stream at sites B and C being classed as SW and HW. These data thus provide evidence for a nested hyporheic flow system occurring along the study reach. A few recent studies (e.g. Wondzell 2006; Poole et al. 2008) have documented nested hyporheic flow paths varying in both length and water residence time, but a nested hyporheic system has not previously been associated with beaver dams. Thus, results from this study suggest beaver can enhance hyporheic exchange at several spatial scales by building multiple dams of varying shapes and sizes.

The findings of this work suggests improved runoff prediction models are needed because enhanced hyporheic flows near beaver dams will increase the length of time stream water is transiently stored within a watershed. Thus hydrologic models need appropriate flow routing algorithms for beaver dammed streams. Traditional routing methods (e.g. kinematic wave and Muskingum methods) (Maidment 1993) are not physically based and therefore, do not account for biological influences on runoff timing. When modeling discharges along beaver dammed streams, there needs to be some other routing function that quantitatively or at least quasi-quantitatively deals with beaver-mediated flow.

5.2 Riparian water chemistry

Riparian water chemistry should reflect the proportion of stream water and groundwater in the hyporheic zone as well as differences in retention time of hyporheic water (Triska et al. 1993). Significant differences in water chemistry were found among riparian wells with differing proportions of surface water and groundwater. NH_4^+ concentrations were significantly greater in GW than in SW classed riparian wells. Also, when the proportion of stream water within the riparian area decreased, NH_4^+ concentrations increased while NO_3^- concentrations decreased. This is likely due to the lack of DO in groundwater (Greenwald et al. 2008), which promotes N to remain in its most reduced form, i.e. NH_4^+. Similarly, hot spots of NH_4^+ developed at site B where there was a high proportion of groundwater in the riparian area, particularly west of the stream. Similar trends have been found by other researchers. For example, Triska et al. (1989) found that NH_4^+ concentrations were highest in groundwater and decreased as hyporheic water was transported closer to the channel where oxic conditions facilitated nitrification. Also, Chestnut and McDowell (2000) found riparian wells with high NH_4^+ concentrations had DO levels below 6% saturation and that these wells were located furthest away from the stream. Unfortunately, field measurements of DO concentrations in hyporheic water were not possible due to equipment failure.

NO_3^- concentrations were generally low throughout the system likely due to low rates of nitrification. Low DO concentrations limit aerobic processes (i.e. nitrification) but favour anaerobic processes (i.e. denitrification and DNRA) resulting in low concentrations of NO_3^- and high concentrations of NH_4^+ (Greenwald et al. 2008), conditions typical of peatlands. Such patterns of riparian chemistry were observed at site B where hot spots of NH_4^+ coincided with NO_3^- and DON cold spots. This suggests that organic N was being mineralized to NH_4^+ and nitrification was limited. Alternatively, any available NO_3^- could have undergone DNRA. Future measurement of gross N production and uptake as well as denitrification would aid in evaluating causes of NO_3^- cold spots. For instance, there may be high NO_3^- production that is tightly coupled to high NO_3^- consumption, as has been shown to occur in boreal peatlands (Westbrook et al. 2004). The NO_3^- hot spots occurring on 23 July may be due to a drop in the water table following the rise in water table from the small rain event that occurred the previous day, which may have enhanced nitrification (Regina et al. 1996; Reiche et al. 2009). Although not measured, denitrification is an unlikely N process at this site, and probably did not contribute to the low NO_3^- concentrations, despite it being a prominent means of NO_3^- removal in other systems (e.g. Hill et al. 2004). This is because peatlands are mostly anaerobic when water tables are high due to low peat permeability and their organic nature (Moore and Roulet 1993; Mitchell and Branfireun 2005). The high water tables (averaging 33 cm below ground) throughout our peat system suggest DO could be low which would limit nitrification. Therefore, denitrification and DNRA may be limited due to a lack of available substrate.

The proportion of stream and groundwater in the riparian area may also influence DOC concentrations, which in turn exerts control on the N dynamics within the hyporheic zone. In an alluvial system, Chestnut and McDowell (2000) found that there was a statistically significant positive relationship between DOC and DON concentrations within riparian wells, and found higher DOC and DON concentrations in wells with a larger percentage of groundwater. A similar relationship between DOC and DON concentrations was found in our riparian area. However, DON and DOC concentrations were relatively high throughout the riparian area probably because depth and degree of decomposition of peat is relatively uniform. These results contrast with Triska et al. (1989) who hypothesized DON and DOC concentrations would be higher in hyporheic water than in stream water.

Beaver dams create different hydrological linkages between the stream and riparian area than do snowmelt or rainfall driven stream flows (Westbrook et al. 2006; Janzen 2008), which lead to the formation of N and DOC hot and cold spots. Cold spots of N and DOC were concentrated upstream of the North dam at site A and along the beaver driven hyporheic flow paths. The beaver induced flow likely caused flushing of N and DOC, which resulted in the formation of cold spots adjacent to the dam and large N and DOC fluxes to the stream below the dam. This is defined by Vidon et al. (2009) as a hot/cold moment paradox, where the riparian zone serves as both a cold spot for biogeochemical transformations and a hot spot for contaminant transport to a stream. Flushing of nutrients from soils along main subsurface flow vectors has been documented in the literature for systems without beaver. For example, Harms and Grimm (2008) found monsoonal flooding in a desert system inundated the riparian area and lead to a net release of C and N to the stream. Others have shown that available substrates are quickly depleted following pulsing flow events due to sequential storms which resulted in a decline in peak nutrient cycling rates (Meixner et al. 2007; Sponseller 2007; Harms and Grimm 2008). Creed et al. (1996) found that a dominant mechanism for producing significant concentrations of N in streams was from rapid flushing of N when the catchment functions as a source of N to adjacent waters, i.e. saturated throughflow rising into previously unsaturated parts of a N-enriched soil profile. This thesis is the first to document that ponded water behind beaver dams increased the exchange of surface water and groundwater which resulted in flushing of N along hyporheic flow paths.

Others have shown that the hyporheic zone acts as a sink for nutrients and that increasing hyporheic exchange decreases nutrient loading to the stream and may in turn improve stream water quality (Allan et al. 2008). For example, Greenwald et al. (2008) found that the hyporheic zone of a peat stream was a net sink for NO_3^- (-1.53 umol m^{-2} h^{-1}) because hypoxic to anoxic conditions in the peat subsurface facilitated denitrification, DNRA, or other NO_3^- uptake processes. Similarly, significant retention or uptake of N and DOC by the hyporheic zone was shown to occur in a tropical stream despite having the potential to increase stream concentrations when calculated using a mass balance approach (Chestnut and McDowell 2000). In contrast, results from this thesis indicate beaver dams increase potential N and DOC fluxes to the stream. Within the study sites, there was an overall net flux of all N forms and DOC to the stream. Perhaps the DOC concentrations downstream of beaver dams in the Adirondacks documented by Margolis et al. (2001), which were about 2 to 3.5 times greater than average DOC concentrations upstream of the dams, could have been the result of flushing along hyporheic flow paths rather than the hypothesized geochemical transformations within the beaver pond.

McClain et al. (2003) conceptualized that the flushing of nutrients from the riparian zone of streams during a storm event encompasses both a hot spot (within the riparian zone) and a hot moment (during the storm event) (Fig. 5.1a). My results show that beaver influenced hyporheic flow pathways may also create hot spots and moments. Data presented herein showed the area below the dam acts as a hot spot due to flushing of N and DOC from the riparian area while the time period over which the stream is dammed results in a hot moment. Since beavers can maintain their dams for decades, hot moments may persist for an extended period of time (Fig. 5.1b). When additional dams are introduced, the magnitude of the hot spot likely magnifies and the hot moment could be maintained until all dams breach by a high discharge event, and the stream is no longer dammed (Fig. 5.1c).

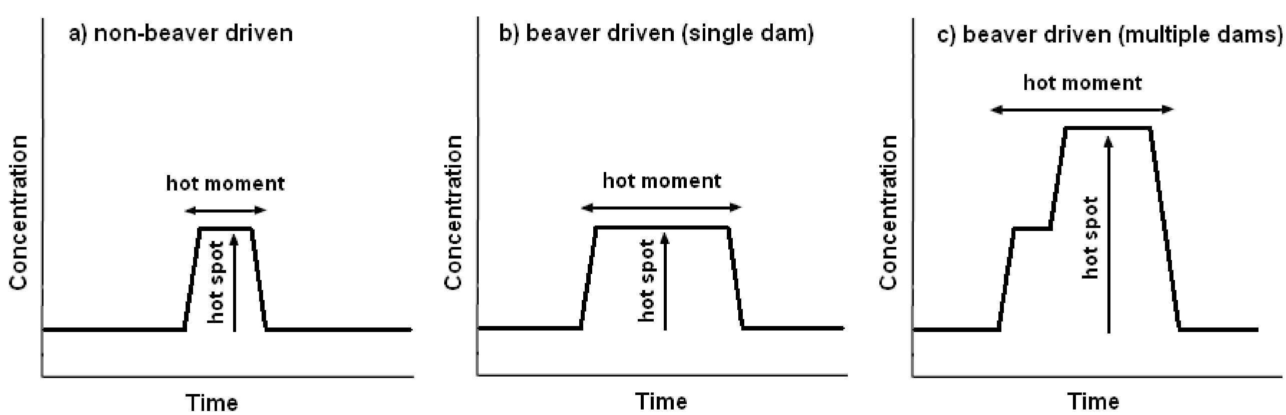

Figure 5.1. Conceptual model of hot spots and hot moments in a) an un-dammed stream where hot spots and hot moments are driven by processes such as episodic rainfall or snow melt events (modified from Harms and Grimm 2008), b) a beaver dammed stream where hot spots and hot moments are driven by a single beaver dam, and c) a beaver dammed stream where hot spots and hot moments are driven by multiple dams. The magnitude of a hot spot is hypothesized to increase by a multiple of n when n beaver dams are present along the stream reach. Hot moments may persist for the duration that the dams are intact, but end when the dams are removed suddenly by large discharge events or slowly by dam abandonment and subsequent degradation.

CHAPTER 6 – CONCLUSIONS

The results from this thesis, conducted within a peat dominated valley in the Canadian Rocky Mountains, show that beaver expand the lateral extent of hyporheic zones by building dams. The hyporheic zone expands by ≤1.5 m in un-dammed reaches due to variations in Q_S, but upwards of 7.5 m or more in dammed reaches. Further, beaver dams regulate stream stage thereby minimizing any sizable fluctuations in riparian water table levels. Resulting constant hydraulic gradients between the stream and riparian aquifer stabilized the size of the hyporheic zone. Thus, results show beaver dams can override the influence that seasonal variations in Q_S may have on hyporheic zone extent because dams drive water further into the bank, at least during the relatively low streamflows studied. Also found was evidence of hyporheic flow paths occurring at multiple scales (i.e. nested hyporheic flow paths) by diverting water further into the riparian area where it may return to the stream further downstream.

This thesis also examined the influence of beaver dams on riparian NH_4^+, NO_3^-, DON, and DOC concentrations in relation to the degree of stream and groundwater mixing. By increasing the size of the hyporheic zone in the riparian area, beaver dams created flow paths that loop around the dam. Coincident with these beaver-driven flow paths were cold spots of N and DOC adjacent to the dam, while hyporheic flows returning to the stream below the dam carried high concentrations of N and DOC. This pattern likely developed due to flushing of N along the beaver driven hyporheic flow vectors. However, the persistence of these beaver driven hot and cold spots is unknown. Long term studies coupled with measurements of N cycling rates will need to be carried out to determine if these beaver driven flow paths may eventually deplete the N in the riparian area and cause nutrient flushing to cease. In such a case, the riparian system may reach a new equilibrium where N availability is low. The results from this thesis contradict those of others who have shown increases in the residence time of water within the hyporheic zone increases N uptake by plants and subsequently decreases N fluxes to the stream (e.g. Findlay 1995, Hill and Lymburner 1998). This thesis showed that where beaver dams are present, the hyporheic zone acts as a potential source of N and DOC to the stream, rather than a sink. A more extensive and detailed longitudinal stream sampling campaign would need to be carried out to examine how beaver driven influxes of N to the stream affect its quality as it moves to a receiving water body.

Research findings indicate that it is important to consider beaver driven hyporheic exchange when predicting streamflows or conducting stream water quality and health assessments in low order basins. Since this thesis shows that beaver dams can enhance hyporheic exchange by driving stream water into the banks, downstream transmission of water may be delayed. Therefore, stream flow attenuation by beaver dams needs to be addressed in current stream flow prediction models.

In many mountain streams, N has been found to be a limiting nutrient and a key driver for primary production (Irvine and Jackson 2006); thus the flux of N to the stream may be important to productivity in these streams Since beaver dams enhance N and DOC fluxes to the stream due to flushing from riparian areas, this may lead to eutrophication or other negative effects on downstream water quality. Beaver populations have been growing since the mid-1900's due to trapping regulations and introductions into new areas (e.g. Tierra del Fuego, Argentina) (Baker and Hill 2003). Therefore, knowledge of watershed-scale beaver populations and the number of beaver dams within a stream network may be essential for effective water quality change detection.

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APPENDIX A – SOIL STRATIGRAPHY

Figure A.1. Soil pit located in the riparian area near site C. Peat is ~62 cm deep here and underlain with gravel (not visible) and gley clay.

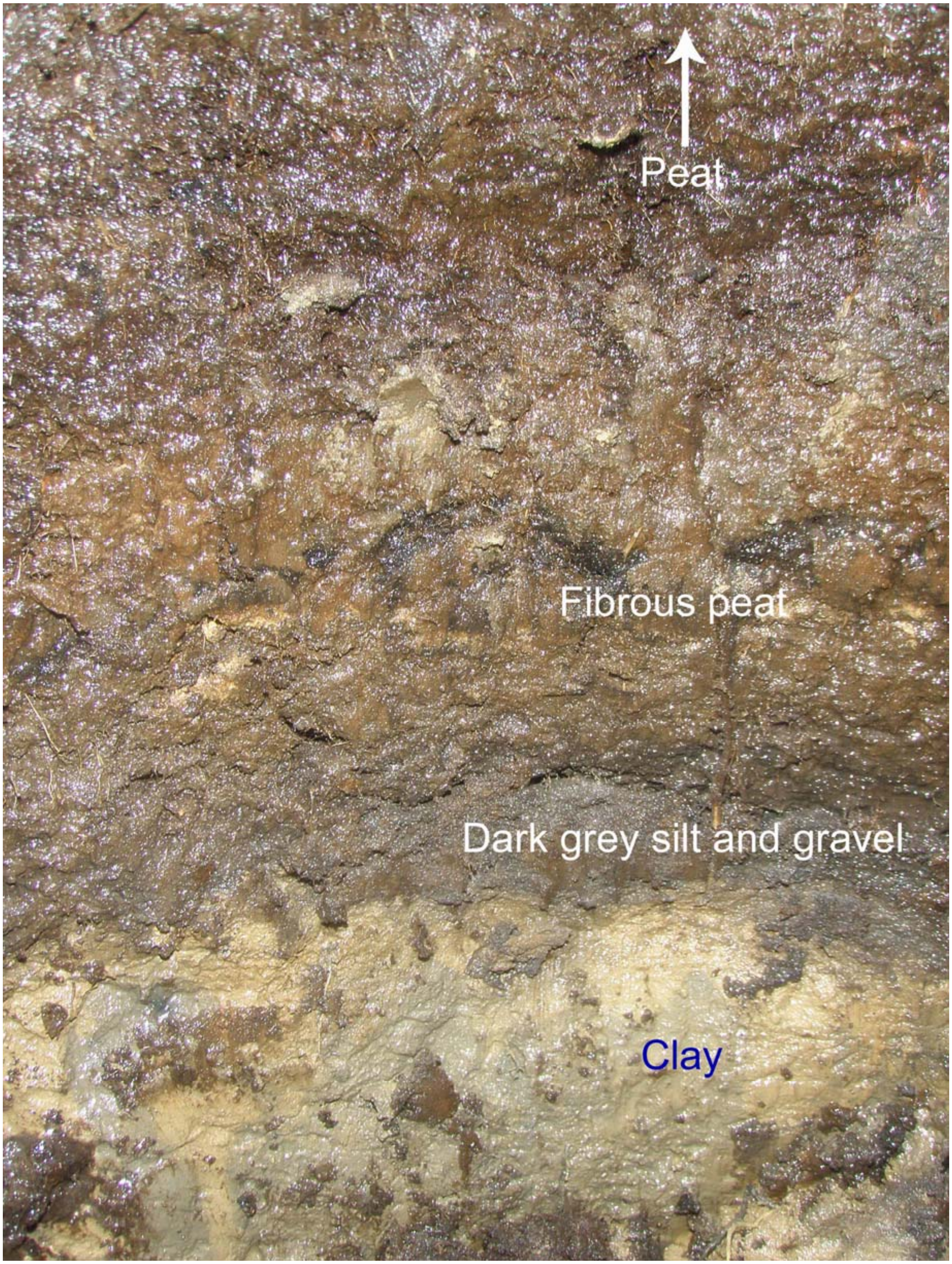

Figure A.2. Soil stratigraphy of riparian area near site C at depths from ~40 to 75 cm in Fig. A.1. Dark brown-black peat is ~48 cm deep, underlain by ~14 cm of more fibrous peat, ~4 cm of dark grey silt and gravel, and >9 cm of gley clay.

APPENDIX B – RATING CURVES

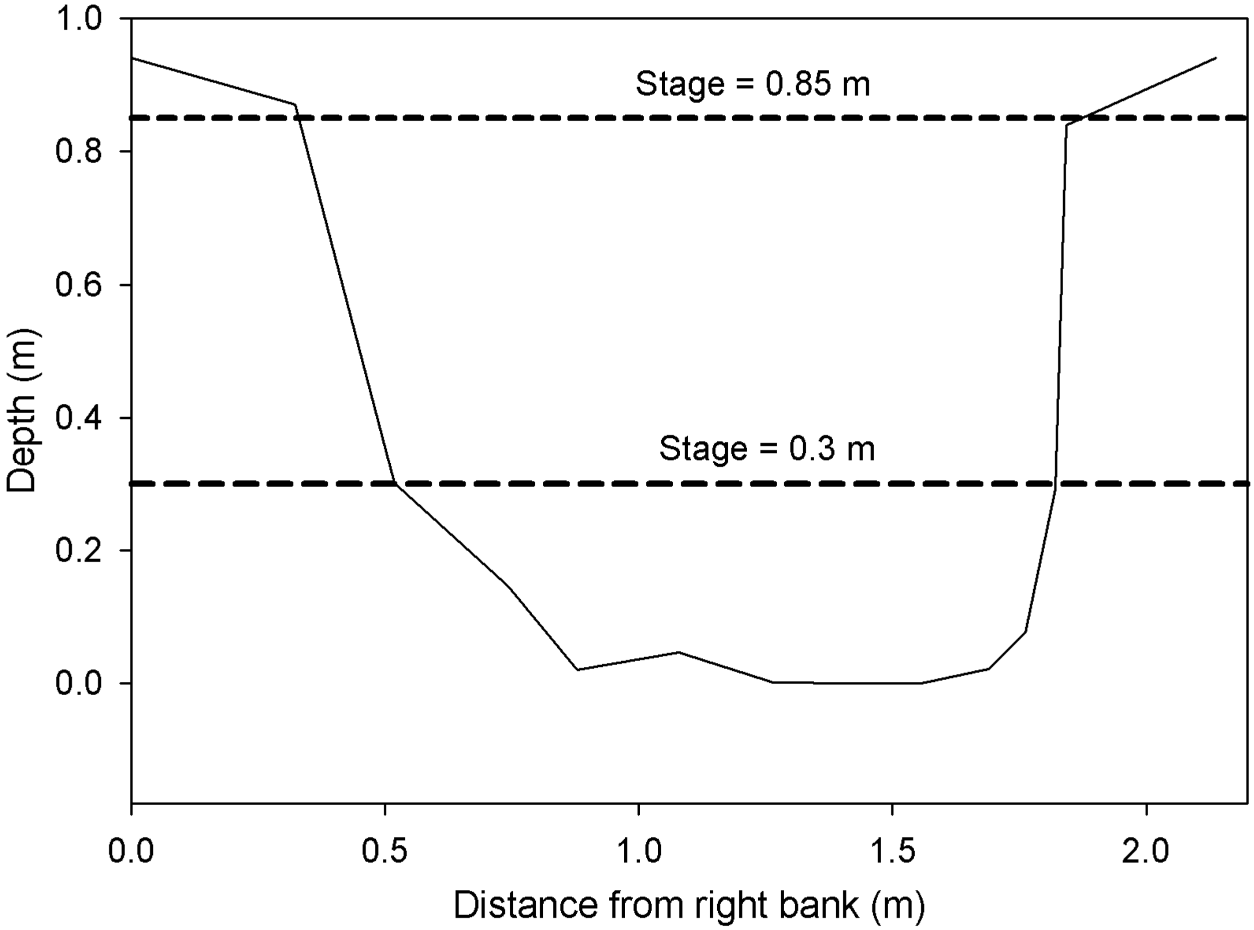

Figure B.1. Cross-section of Bateman Creek where stream gauging was carried out. Stages 0.3 and 0.85 m were significant in determining stage-discharge relationships (see Fig. B.2).

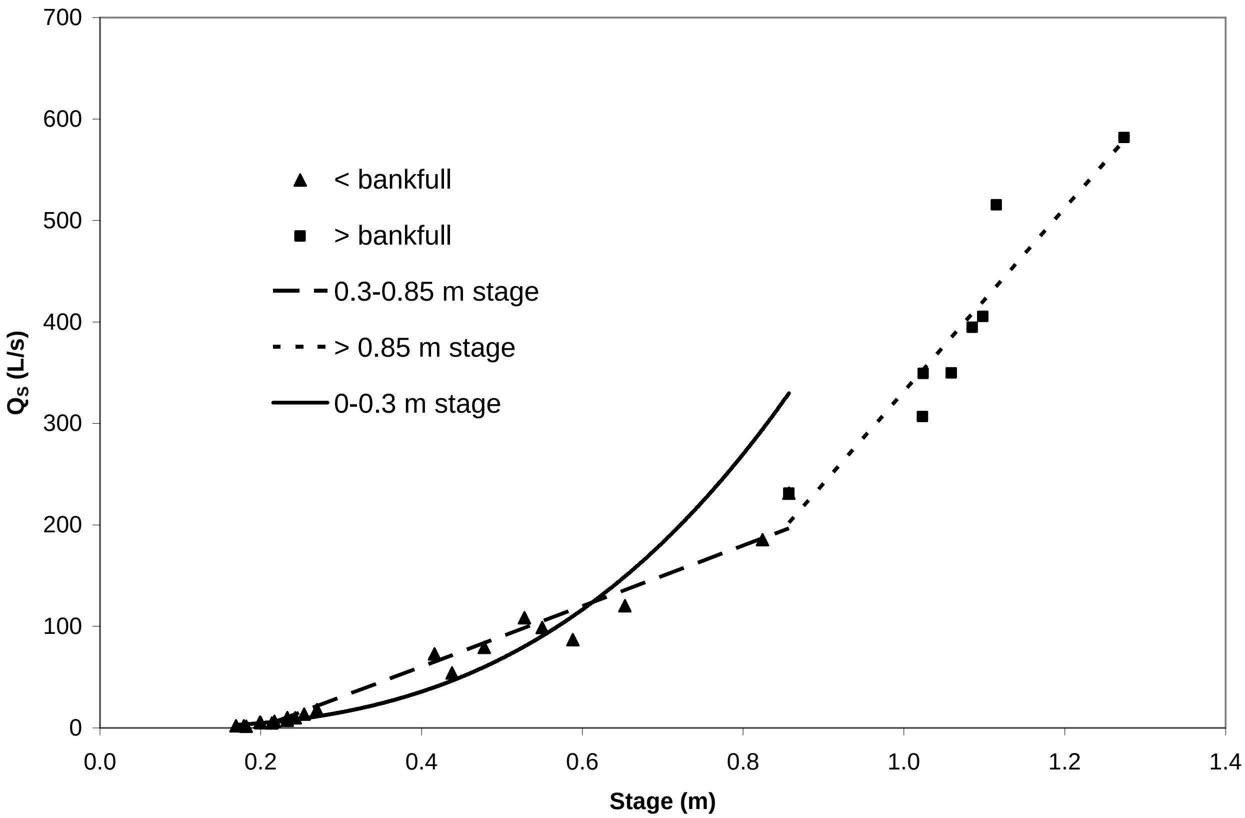

Figure B.2. Stream discharge rating curves for above bankfull stage (>0.85 m) with an r^2 value of 0.88 (Q_S=904.01stage – 572.67), stage 0.3 to 0.85 m with an r^2 value of 0.96 (Q_S=298.04stage – 58.90), and stage <0.3 m with an r^2 value of 0.95 (Q_S=517.34680stage$^{2.92}$).

APPENDIX C – CHLORIDE STANDARD CURVES

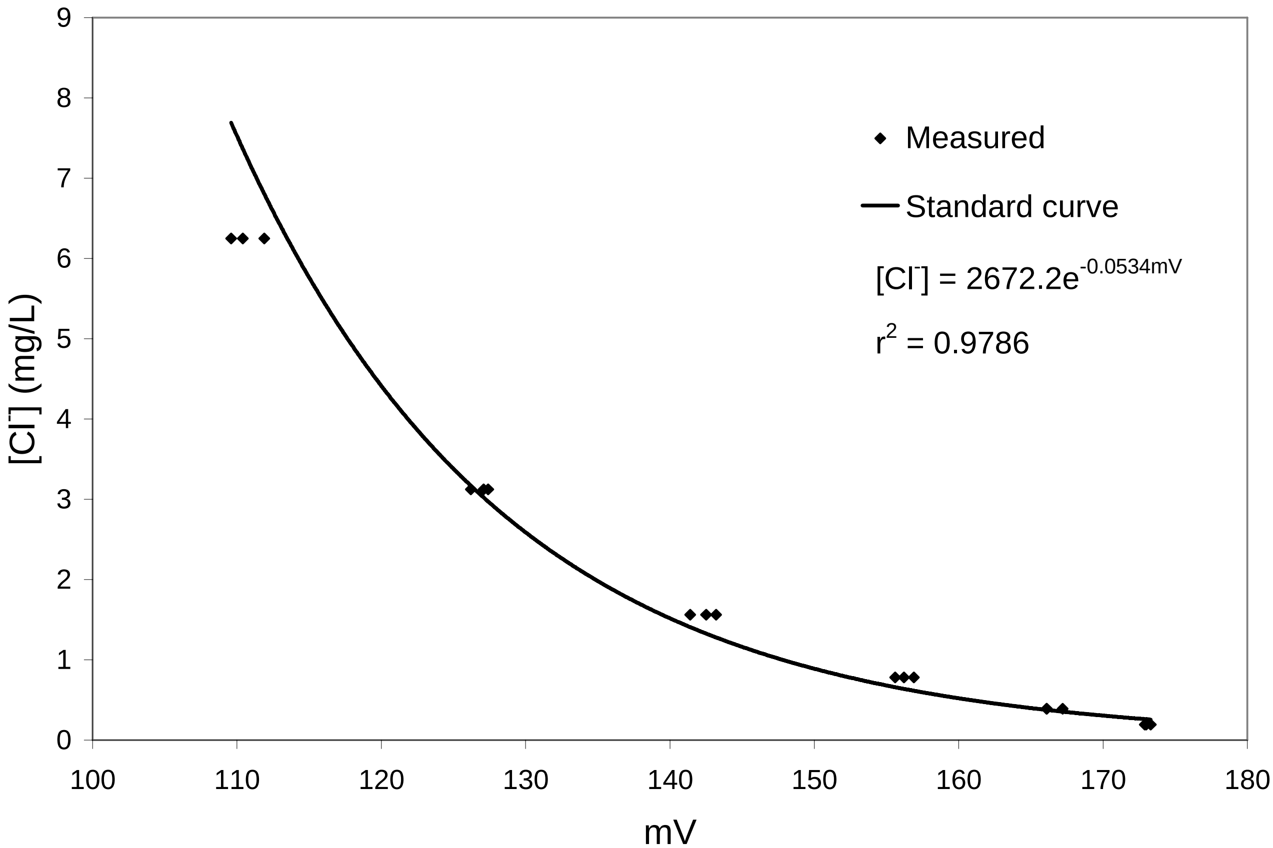

Figure C.1. An example standard curve (24 October 2008) used to estimate Cl^- concentrations from voltage measurements for known concentrations of Cl^-. See methods chapter for details.

APPENDIX D – SATURATED HYDRAULIC CONDUCTIVITIES

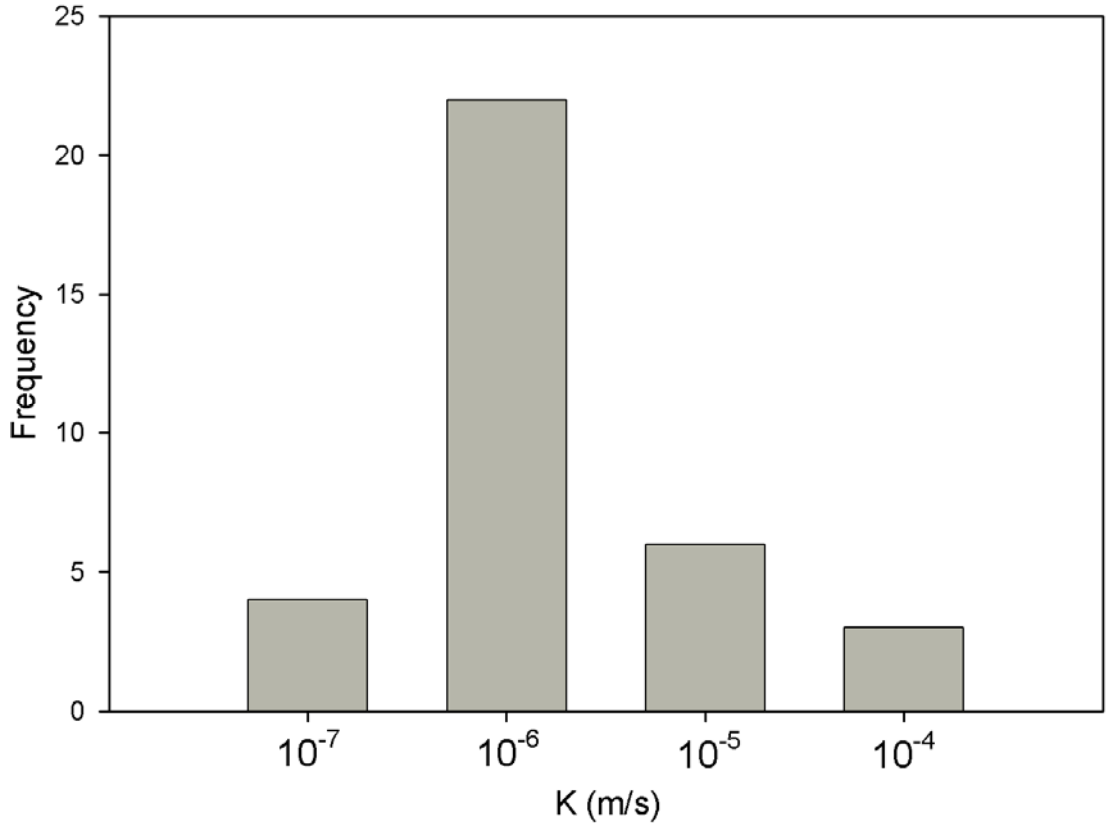

Figure D.1. The range of riparian well hydraulic conductivity (K) estimated using the Hvorslev method (n=35).